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A GIS-based Multi-Criteria Decision Analysis of Wind Farm Site Suitability in New South Wales, Australia, from a Sustainable Development Perspective

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Abstract

The interest for renewable energy within Australia is growing and the New South Wales (NSW) Government has committed to a Renewable Energy Target scheme of 20 percent renewable energy by 2020. Wind energy is a mature renewable energy resource, which has been successfully deployed for electricity generation around the world, including Australia. It is further believed to be a viable option to help expand the renewable energy market in NSW.

In this study, wind farm site suitability in NSW is evaluated from a sustainable development perspective, and by application of geographic information systems (GIS) and multi-criteria decision analysis (MCDA). As such, this project aims to develop a decision support tool to assist in wind farm planning by incorporating economic, environmental and social aspects of wind farm siting.

The defined decision criteria include decision constraints and decision factors, of which the latter are standardised using primarily fuzzy logic. The MCDA implements a weighted linear combination method, with relative weights derived from pairwise comparisons based on the analytic hierarchy process. Furthermore, three policy scenarios are investigated: equal weights, environmental/social priority and economic priority. A suitability index (SI) for each scenario is presented, detailing the degree of suitability ranging between zero (0), not suitable location, and one (1), ideal location. Additionally, this study attempts to identify priority areas, defined as areas of particular interest for further investigation, as well as the most suitable locations for wind farm development.

The final suitability index for each policy scenario indicates that the majority of the study area (approximately 70 percent) is considered 'acceptable' ($0.50 < SI \leq 1$) for wind farm development, with a varying, but relatively widespread, degree of 'high suitability' ($SI > 0.75$). The local government areas of Conargo and Jerilderie are considered priority areas in all three investigated policy scenarios, and the most suitable locations are located within the local government areas of Goulburne Mulwaree, Mid-Western Regional, Oberon, Upper Lachlan Shire and Wingecarribee. Moreover, the majority of existing wind farms are found within 'high suitability' areas ($SI > 0.75$), and eight out of eleven existing wind farm locations are situated within areas deemed to be 'acceptable' ($SI > 0.5$). However, it should be noted that two wind farms (CSIRO Energy Centre Wind Facility and Hampton Wind Park) do not meet the decision constraint criteria defined in this study.

In conclusion, the results of this study indicate great development potential for wind energy in NSW; and the here presented decision support tool could potentially assist wind farm developers and governments within a planning or decision making context in NSW.

Keywords: Geography, GIS, MCDA, wind farm, site suitability, Australia

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List of Abbreviations

AHP	Analytic hierarchy process
AUD	Australian dollars
CEEC	Critically endangered ecological communities
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DFMF	Decreasing fuzzy membership function
GDA	Geocentric Datum of Australia
GIS	Geographic information systems
IFMF	Increasing fuzzy membership function
ISO	International Standards Organisation
LGA	Local government area
MCDA	Multi-criteria decision analysis
MF	Membership function (fuzzy sets theory)
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NPWS	National Parks and Wildlife Services
NSW	New South Wales
SEDA	Sustainable Energy Development Authority
SEPP	State Environmental Planning Policy
SI	Suitability index
WLC	Weighted linear combination

List of Units

m	Metre
m/s	Metre per second
km	Kilometre
km^2	Square kilometre
MW	Megawatt
GW	Gigawatt

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1. Introduction

Changes in the global climate system are today evident and have been linked to increases in anthropogenic induced radiative forcing, in particular emissions of carbon dioxide from burning of fossil fuels (Intergovernmental Panel on Climate Change, 2013). According to the Department of Industry and Science (2015a), the use of coal, oil and natural gas accounts for over 85 percent of total electricity generation in Australia, and *The Green Innovation Index: International Edition*, published by Next 10 (2015), ranks Australia among the worst in the world for per capita greenhouse gas emissions. However, the renewable energy market in Australia is growing and the New South Wales (NSW) Government has committed to a Renewable Energy Target scheme of 20 percent renewable energy by 2020, with respect to electricity generation (Department of Resources & Energy, 2014).

Wind energy is a mature renewable energy resource, which has been successfully deployed for electricity generation in over 80 countries around the world, with an estimated global wind capacity of 432.9 gigawatt (GW) by the end of 2015 (Global Wind Energy Council, 2015). Furthermore, wind energy is considered one of the most environmentally friendly and economically viable forms of renewable energy (Latinopoulos & Kechagia, 2015); and according to Wiser et al. (2011) the expansion of wind farm developments may represent a crucial aspect of climate change mitigation and reduction of greenhouse gas emissions.

In the year 2013/2014, 14.8 percent of Australia's electricity generation was produced from renewable sources, with wind energy accounting for 4.1 percent (Department of Industry and Science, 2015a). Furthermore, the Department of Industry & Science (2015b) reports that only 1.3 percent of NSW total electricity generation was produced from wind energy in 2013/2014. The state of NSW in Australia has however excellent wind resources by international standards (Coppin et al., 2003), and wind energy is hence believed to represent a viable option to further develop the renewable energy market in NSW.

Nevertheless, at present, the expansion of wind energy utilisation concerns land-use planning and thus involves two apparently contradictory objectives: economic profitability and nature conservation, both related to the concept of sustainable development (Van Lier, 1998). This can further be explained by the fact that a wind farm location must provide a sufficient wind resource in order to be viable; however, it must also inhibit other characteristics which make the development technically and economically feasible, whilst at the same time ensure protection of environmental and social values (Baban & Parry, 2001). As such, the suitability of a wind farm location is subject to multiple criteria covering economic, environmental and social aspects.

Geographic information systems (GIS) are computer based systems which are designed to store and process geographic information. They are today recognised as a powerful tool, with advanced methods and techniques, often used within spatial planning and management (Hansen, 2005). Furthermore, according to Longley et al. (2011), GIS is sometimes referred to as a spatial decision support system due to its ability to solve problems with multiple objectives or criteria.

Multi-criteria decision analysis (MCDA) can be described as a 'collection of techniques and procedures for structuring decision problems, and designing, evaluating and prioritising alternative decisions' (Malczewski, 2006, p. 703). Since GIS have the ability to incorporate and analyse multiple spatially related criteria in a decision-making context, the combination of GIS and MCDA can be described as a process which transforms and combines geographical data and value judgments in order to obtain information for decision making (Malczewski, 2006). As such, by implementing a MCDA model within a GIS environment, a decision support tool aiming at evaluating wind farm site suitability could be generated.

Over the last decade, a number of studies have been conducted to assess wind farm site suitability based on the application of MCDA within a GIS environment in various locations including: the United Kingdom (Baban & Parry, 2001), the Baltic Sea region (Hansen, 2005), Thailand (Bennui, 2007), Turkey (Aydin et al. 2010), the New York State (Van Haaren & Fthenakis, 2011) and Greece (Latinopoulos & Kechagia, 2015). However, to the author's knowledge, no such research has yet been undertaken for the state of NSW in Australia. The present study therefore introduces a GIS-based MCDA approach to evaluate wind farm site suitability across on-shore areas of NSW, which can assist wind farm developers and governments within a planning or decision making context. Furthermore, this study is believed to be unique with respect to the extent of the study area incorporated into the GIS-based MCDA.

1.1 Project Aim and Research Questions

The aim of this study is to develop a decision support tool to assist wind-farm planning in NSW from a sustainable development perspective, incorporating economic, environmental and social aspects. More specifically, the project attempts to address the following questions:

1. Is it possible to identify priority areas, as well as the most suitable locations, for wind farm development in NSW based on the developed decision support tool?
2. How sensitive is the developed decision support tool to changes in policy priorities (environmental/social priority and economic priority)?
3. To what degree are the currently licensed wind farm sites located within areas identified as 'acceptable' according to the developed decision support tool?

2. Background

2.1 Wind Energy Basics

Wind is air movement caused by the uneven heating of the Earth by the sun, as well as the Earth's own rotation. The differences in temperature result in differences in air pressure, and wind is generated from the system's endeavour to maintain equilibrium. The greater the pressure difference is, the faster the wind blows. Wind energy is the kinetic energy of moving air, where the amount of kinetic energy theoretically available increases with the cube of wind speed. Generally, wind speed increases with height above ground level due to reduced friction from the Earth's surface (Sustainable Energy Development Authority [SEDA], 2001).

Moreover, wind speed at a certain location is influenced by a number of factors including: the geographic location and prevailing synoptic weather pattern; regional terrain where, for example, hills, ridges and mountains can increase the wind speed; surface roughness, which can affect both wind speed and turbulence (which further reduces the ability to capture wind energy); and obstacles to the wind such as buildings and forests, which may increase the turbulence and lower wind speed (Australian Greenhouse Office & Australian Wind Energy Association, 2004).

Wind energy can be used to generate electricity by the use of wind turbines. The movement of air over the blades on a wind turbine results in pressure differences and turning of a rotor. The rotor is in turn connected to a generator, which converts the mechanical energy produced by the blades and the rotor into electrical energy or electricity. Today, the conventional horizontal axis wind turbine typically consists of four main elements: rotor, nacelle (houses the generator and gearbox), tower and footing, see Figure 1 (SEDA, 2001). Most turbines have a three-bladed rotor that operates upwind of the tower and at variable speed. The variable wind speed turbines start to produce electrical energy at a specific 'cut-in' wind speed, often between 3 to 4 m/s, where the rotor speed increases with increasing wind speed until it reaches its maximum design wind speed where it 'cuts-out', typically around 20 to 25 m/s, to minimise any risks of overload and component damage (Wiser et al., 2011).

Although the concept of wind energy has been used for millennia, the commercial production of electricity from wind turbines did not become viable until the 1970's (Wiser et al., 2011). Since the 1980s there has been a continuing trend towards larger wind turbines and higher power ratings (maximum electrical power output). Today's wind turbines often have rotors exceeding 80 m in diameter and towers exceeding 80 m in height, with a rated output of 1.5 megawatt (MW) or greater (Wiser et al., 2011). Navigant Research (2015) reports that in 2014, the average size of installed wind turbines around the world was estimated to 1.958 MW.

Furthermore, groups of wind turbines installed to generate electricity are commonly referred to as *wind farms*. At present, wind farms often have a total installed capacity of 5 to 300 MW (Wiser et al., 2011).

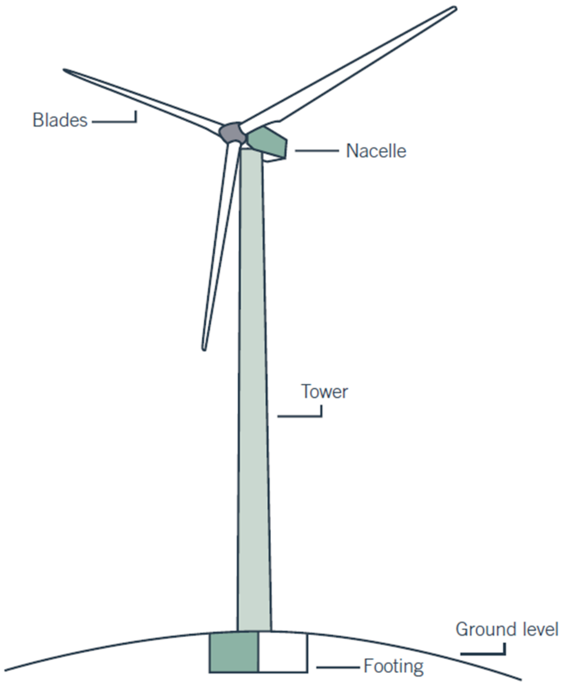

Figure 1. Illustration of a typical wind turbine (SEDA, 2001).

The electricity generated from wind turbines is typically linked to the electricity network or ‘grid’, via a transformer and substation, or to off-grid applications in remote areas (Geoscience Australia & ABARE, 2010). The grid is made up of the transmission, sub-transmission and distribution networks, which carry the electricity from power generators to customers (Short, 2004). High voltage transmission lines can carry the power for hundreds of kilometres before it is transformed to low voltage and distributed to costumers. However, the energy losses in transmission increases with distance, and it is therefore of interest to locate wind farms close to the grid, as well as close to major energy consumption areas (urban/industrial areas i.e.). In Australia, wind farms are generally installed within 30 kilometres (km) of the transmission network; however, wind farm locations at a distance of up to 100 km from the transmission network have been proposed (Geoscience Australia & ABARE, 2010). According to Krohn (2009), large wind farms are generally connected to the high voltage transmission network, whereas individual wind turbines or smaller wind farms are often connected to the high-voltage distribution network.

Furthermore, the approach of centralised generation and long distance transmission has, in recent decades, become less attractive due to the economic costs and negative environmental impacts, which in turn has resulted in a growing interest for decentralised energy systems. Decentralised energy can be described as energy technologies and practices that optimise the use of local resources, such as wind energy, whilst reducing the need for large-scale transmission networks (Dunstan et al., 2011). As such, wind energy could be transferred to a localised electricity distribution network as part of a decentralised energy strategy.

The amount of electricity a wind farm can generate depends on the available energy, primarily determined by the wind speed at the site, but also on the number of installed turbines; the turbines performance characteristics in the wind conditions at the time; and the amount of time they are operating (SEDA, 2001).

Current research and technical advances within wind turbine development have produced more powerful rotors, larger blades, improved power electronics, better use of composite materials and taller towers, which has resulted in an increased energy yield and significantly lower noise levels i.e. (Jäger-Waldau & Ossenbrink, 2004; Herbert et al., 2007). Future wind energy technology advances are anticipated to further improve turbine design procedures, increase materials usage efficiency, reliability and energy capture, whilst reducing operating and maintenance costs and providing longer lifetime for the components (Wiser et al., 2011).

2.2 Wind Farm Planning Framework in New South Wales

Currently, the suitability of a potential wind farm location in NSW is assessed independently as part of a development proposal and with reference to the *Draft NSW Wind Farm Planning Guidelines* (Department of Planning & Infrastructure, 2011), which provides the current legislative framework and guidelines for wind farm developments within the State. Local wind farm developments (less than 5 million Australian dollars [AUD]) are assessed and determined by the council, whilst regional developments (5 to 30 million AUD) are assessed by the council and determined by the relevant Joint Regional Planning Panel. State significant developments, which are developments with a capital investment value of 30 million AUD or more (or 10 million AUD in an environmentally sensitive area), is assessed by the Department of Planning and Infrastructure and determined by the independent Planning Assessment Commission (Department of Planning & Infrastructure, 2011).

Electricity generating works (including wind farms) are classified as ‘permitted with consent’ in Clause 34 of *State Environmental Planning Policy (Infrastructure) 2007* within the following land use zones: RU1 Primary Production; RU2 Rural Landscape; RU3 Forestry; RU4 Rural Small Holdings; IN1 General Industrial; IN3 Heavy Industrial; SP1 Special Activities; and SP2 Infrastructure. Wind farms may also be permitted in other land use zones in accordance with the council’s ‘Local Environmental Plan’ (Department of Planning & Infrastructure, 2011).

Key considerations in the assessment of wind farm development applications include: proximity of turbines to existing residential dwellings; community consultation; visual amenity; noise; health; decommissioning; auditing and compliance. The guidelines further describe that environmental aspects should be included in an environmental impact statement, or statement of environmental effects, depending on the magnitude of the proposed development. Relevant assessment issues include: landscape and visual amenity; social aspects (noise and electromagnetic interference i.e.); ecological aspects; economic aspects (mineral resources i.e.); aboriginal and European heritage; hazards and risks (aircraft safety and bushfire hazard i.e.); and construction, including traffic and transport issues. Additionally, ecological issues should cover vegetation type and condition; sensitive environments; and threatened species, populations and ecological communities (Department of Planning & Infrastructure, 2011).

The former NSW government agency SEDA has previously released a NSW wind atlas detailing the annual average wind speeds at a height of 65 m above ground level across NSW as a preliminary tool for wind farm siting (Coppin et al., 2003). Furthermore, a wind resource map detailing wind speed at 100 m above ground level has recently been published by the NSW government organisation Geological Survey of NSW (Wade et al., 2016).

2.3 Aspects of Sustainable Wind Farm Development

Sustainable development can be defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs', from the report *Our Common Future* published by the World Commission on Environment and Development (1987, p.43). Additionally, the concept of sustainable development recognises that there are three dimensions of sustainability which have to be considered: economic, environmental and social (Sundström & Rydén, 2003). Therefore, from a sustainable development perspective, wind farm development hence incorporates economic, social and environmental aspects, which all have to be considered in the planning context.

Key economic factors for wind farm development include wind speed, and distance to the grid network and roads (Baban & Parry, 2001; Clean Energy Council, 2013). According to Krohn (2009) and with respect to the installation of a medium-sized wind turbine (1.5 - 2 MW), the grid connection cost accounts for about 2 to 10 percent of the total installation cost and road construction for about 1 to 5 percent. Moreover, physical factors such as slope gradient and land cover affect the technical feasibility and hence economic profitability. Soft soils and rock can increase the foundation cost significantly (Bile, 2010), and ground conditions should therefore also be considered from an economic aspect. According to Krohn (2009), the foundation cost generally represents around 1 to 9 percent of the total cost for a medium-sized wind turbine. Furthermore, the general installation cost of wind turbines is further influenced by the turbine size, country of installation and land ownership structure (Krohn, 2009).

From an environmental perspective, potential negative impacts of wind farm developments include: bird and bat collisions; habitat and ecosystem modifications, such as destruction and fragmentation of native vegetation and habitats; impacts on bird feeding, breeding and foraging behaviour; introduction of weed species; soil erosion; and changes to the local weather and regional climate (Dai et al., 2015).

Potential negative social impacts of wind farm developments include: visual amenity (aesthetics); noise; shadow flicker; blade glint; night lighting; electromagnetic fields; other health and safety issues; and property value impacts. According to Wiser et al. (2011), noise is the most prominent nuisance impact. However, a survey by the Department of Environment, Climate Change & Water (2010) found that 85 percent of the residents support wind farm developments in NSW, with only 17 percent of supporters concerned about noise impacts and 11 percent concerned about visual impacts on the landscape. The majority of residents were also supportive of wind farms being established in the vicinity of their residence, with 60 percent supporting wind farm developments within a distance of 1-2 km. Furthermore, wind farm developments have the potential to impact features of cultural and archaeological value. The aspect of public safety could also be considered a social aspect, which in this case would include hazards and risks such as 'blade throw', aviation safety and bushfire risk (Department of Planning & Infrastructure, 2011).

Appropriate siting of wind farms is deemed the most important strategy to optimise economic viability, whilst mitigating any negative impacts. However, several other technologies and strategies can also be applied to further reduce environmental and social impacts. These include: blade design, application of coloured blades, use of special gearboxes, and slowing of the rotational speed in order to reduce noise impact and visual disturbance; the use of larger blades and slower rotor speed to reduce bird mortality; the use of synthetic materials or installation of extra transmitter masts to minimise any electromagnetic interference; appropriate siting of individual wind turbines to reduce shadow flicker; and proper turbine spacing and pattern to reduce any hydro-meteorological impacts (Wiser et al., 2011; Dai et al., 2015).

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3. Study Area

The here investigated study area covers the state of NSW in south-eastern Australia (off-shore areas excluded). The size of the mainland area is approximately 800 570 km^2 and includes 152 local government areas (LGAs), as well as an area identified 'unincorporated' region in the Australian Bureau of Statistics LGA structure. The human population at the end of June 2015 was estimated to 7.6 million, with the highest population density along the coast (Australian Bureau of Statistics, 2016).

The overall topography and terrain throughout NSW is complex and includes landforms such as mountain ranges, rock features, table lands, water bodies and coastal features. The land cover varies significantly between different regions and landscapes; however, includes cultivated and managed lands, forbs and graminoids (grasses), shrubs, chenopods and trees. The highest mountain is Mt Kosciuszko with a height of 2228 m (Geoscience Australia, 2016). Land use within the state includes, but is not limited to, rural and agricultural land, built-up areas, recreational and conservation areas, mining and quarrying, transport, and power generation and distribution (Department of Agriculture and Water Resources, 2016). A map of the study area is provided in Figure 2 detailing populated places, LGA boundaries and the state capital of Sydney.

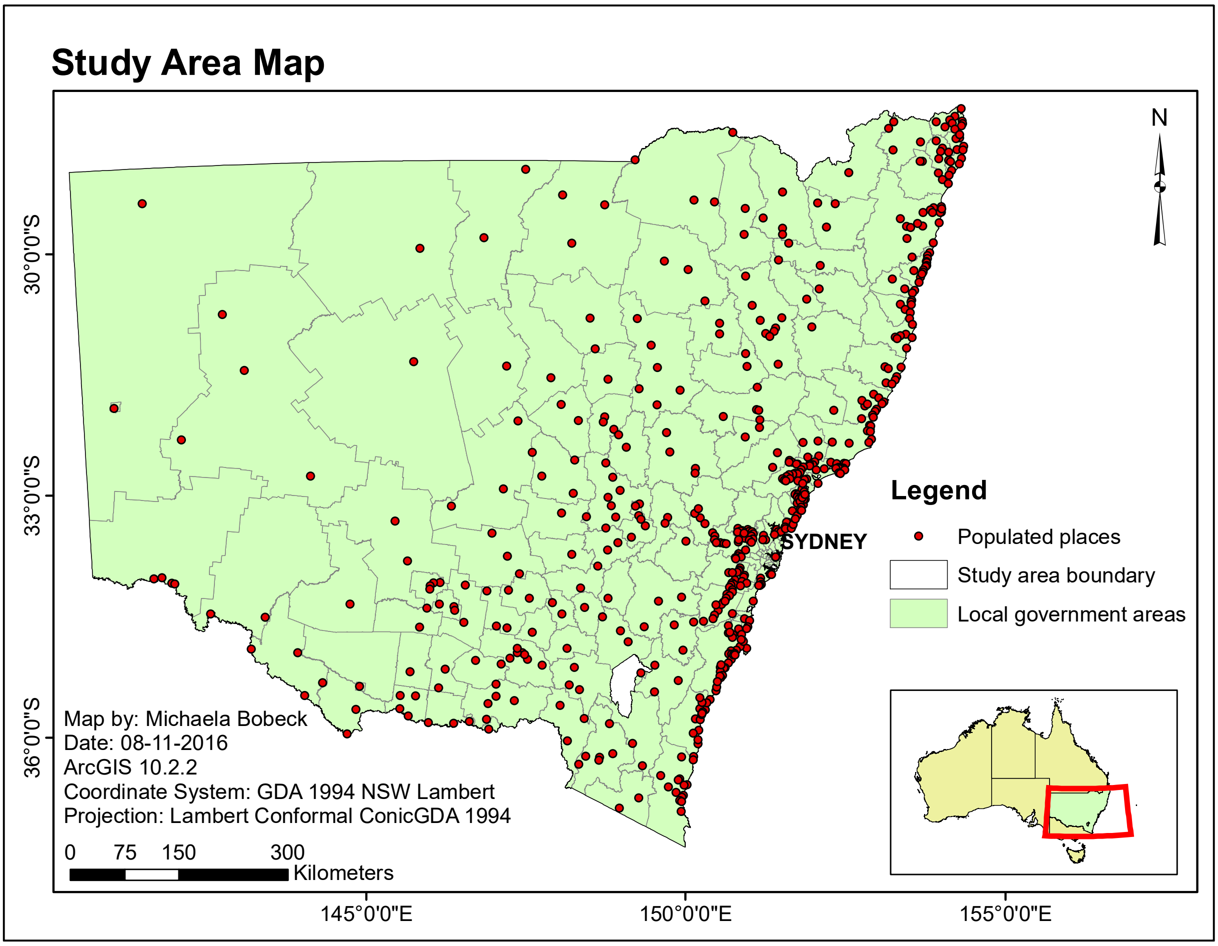

Figure 2. Map of study area covering the mainland area of NSW, Australia.

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4. Methodology

4.1 Identification of Decision Criteria

The wind farm planning process often incorporates complexity, uncertainty, multiple management objectives and various spatial data attributes. Moreover, in order to assess the degree of suitability for a certain potential location, most decision-making processes generally consider multiple criteria. As such, it is proposed that the suitability of a location should be expressed based on both Boolean and fuzzy logic (Hansen, 2005).

In this study, *decision criteria* consist of constraints and factors, which, as described by Eastman et al. (1993), represent quantifiable attributes to assist the decision-making process. Moreover, the overall objective of the decision criteria identified in this study is to evaluate wind farm site suitability from a sustainable development perspective, covering economic, environmental and social aspects. The criteria were established based on previous scientific publications and the current legislative framework in NSW as described in the *Draft NSW Wind Farm Planning Guidelines* (Department of Planning & Infrastructure, 2011).

Decision constraints are based on Boolean criteria (true/false) and aim to exclude areas deemed 'unfeasible' for wind farm development (Hansen, 2005). Therefore, exclusion zones (unfeasible areas) are denoted a value equal to zero (0) whilst potential development sites (feasible areas) are denoted a value equal to one (1). *Decision factors* on the other hand are evaluation criteria, which aim to describe the degree of suitability for the alternative wind farm locations (grid cells) considering the respective attribute (Hansen, 2005). The factors can thus be represented as fuzzy sets, where continuous degrees of fuzzy membership are defined over a range of real numbers [0, 1], as described in the fuzzy sets theory introduced by Zadeh (1965).

The fuzzy sets theory recognises that multiple classes or sets can be present simultaneously and that the degree of each class's presence is described as a membership value. Moreover, the fuzzy sets theory provides a framework for dealing with uncertainty by allowing the 'grouping of individuals into classes without sharply defined boundaries', which is suitable when describing 'ambiguity, vagueness and ambivalence in models of empirical phenomena' (Hansen, 2005, p. 79). According to the fuzzy sets theory, the degree of membership of an object z in a fuzzy subset A can be expressed as a membership value between zero (0) and one (1), and defined by the application of a membership function (MF) (Zadeh, 1965). There are numerous types of membership functions to describe fuzzy sets; however, in this study a linear function was used. A linear function was deemed appropriate for the representation of the presumed relationship between site suitability and distance from attributes, defined in the set of decision factors. Moreover, a linear function was also applied in the studies by Hansen (2005), and Latinopoulos and Kechagia (2015).

Furthermore, the present study distinguishes between two types of linear functions: an increasing fuzzy membership function (IFMF), illustrated in Figure 3, and a decreasing fuzzy membership function (DFMF), illustrated in Figure 4, the latter in which lower values of z in a certain subset A are more suitable than higher values of z. For example, wind farm sites with *higher* wind speeds are *more* suitable (IFMF), whereas wind farm sites with *higher/greater* slopes are *less* suitable (DFMF). It should also be noted that the MF has two threshold values or control points: 'q' indicating the least suitable value of z, where the grade of membership is not satisfied and hence has a membership value equal to zero (0); and 'p' indicating the value of z where the grade of membership is fully satisfied and hence has a membership value equal to one (1). The mathematical expressions for the IFMF and DFMF used in this study are presented in Equation 1 and 2 below.

$$\boldsymbol{IFMF}(\boldsymbol{z_i}) = \begin{cases} \mathbf{0} & \text{for } \boldsymbol{z_i} < \boldsymbol{q_i} \\ \frac{z_i - q_i}{p_i - q_i} & \text{for } \boldsymbol{p_i} \leq \boldsymbol{z_i} \leq \boldsymbol{q_i} \\ \mathbf{1} & \text{for } \boldsymbol{z_i} > \boldsymbol{p_i} \end{cases} \qquad \text{Equation 1.}$$

$$\boldsymbol{DFMF}(\boldsymbol{z_i}) = \begin{cases} \mathbf{1} & \text{for } \boldsymbol{z_i} < \boldsymbol{p_i} \\ \frac{z_i - q_i}{p_i - q_i} & \text{for } \boldsymbol{p_i} \leq \boldsymbol{z_i} \leq \boldsymbol{q_i} \\ \mathbf{0} & \text{for } \boldsymbol{z_i} > \boldsymbol{q} \end{cases} \qquad \text{Equation 2.}$$

To summarise, decision factors, established to evaluate wind farm site suitability, can be expressed with a membership value ranging from zero (0), not suitable location, to one (1), ideal location, a process also referred to as *standardisation* of factors. In this study, decision factors are standardised primarily by the application of the fuzzy sets theory; however it should be noted that some of the established decision factors involve qualitative attribute data and these are therefore standardised using a six point Likert-type scale or a binary scoring system.

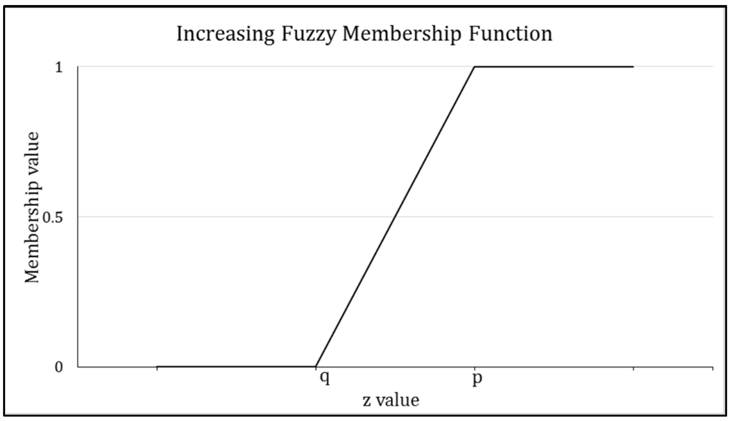

Figure 3. Increasing fuzzy membership function (IFMF).

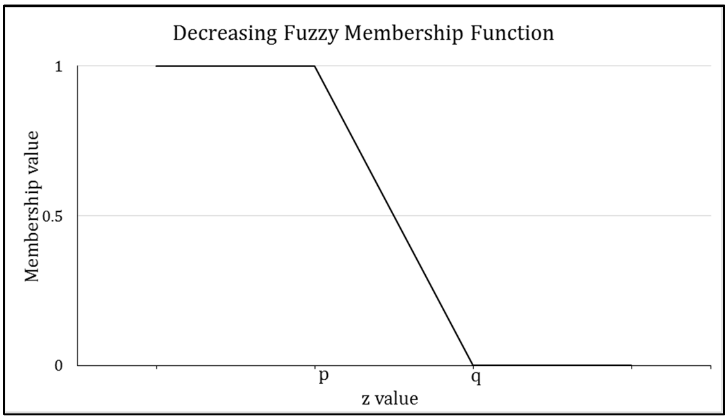

Figure 4. Decreasing fuzzy membership function (DFMF).

4.1.1 Description of Decision Constraints

In this study, six decision constraints (C1-C6) were identified, which are discussed below and summarised in Table 1.

C1. Wind speed: Wind turbines typically start to produce electricity at around 4 m/s (Department of Planning & Infrastructure, 2011); however, previous scientific publications commonly apply a threshold value of 4.5 m/s (Latinopoulos & Kechagia, 2015) or 5 m/s (Baban & Parry, 2001). In this study, areas with a modelled wind speed lower than 5 m/s were deemed unfeasible for wind farm development and hence excluded.

C2. Built-up areas: Previous scientific publications detail various setback distances from built up areas and settlements, ranging between 500 and 2000 m depending on the type of area (large city, town i.e.) or number of residents (Baban & Parry, 2001; Hansen, 2005; Aydin et al., 2010; Latinopoulos & Kechagia, 2015). Furthermore, the Draft NSW Wind Farm Planning Guidelines (Department of Planning & Infrastructure, 2011) describes that any wind farm development proposal within a 2000 m radius of existing residences requires additional assessment in the context of visual amenity, blade glint, shadow flicker, health issues and noise. For the purpose of this study, built-up areas (incorporating populated places and towns), including a 2000 m buffer, were deemed unfeasible for wind farm development and hence excluded.

C3. Land use restrictions: In this study, all land use zones not classified as 'permitted with consent' in Clause 34 of *State Environmental Planning Policy (Infrastructure) 2007* were deemed unfeasible for wind farm development and hence excluded. Subsequently, only the following land use zones were considered feasible, in accordance with Department of Planning & Infrastructure (2011): IN1 General Industrial; IN3 Heavy Industrial; RU1 Primary Production; RU2 Rural Landscape; RU3 Forestry; RU4 Rural Small Holdings; SP1 Special Activities; and SP2 Infrastructure.

C4. Environmental protection: In order to protect the natural environment, wind farms should not be located in protected areas such as national parks, nature reserves or state conservation areas. Baban and Parry (2001) identified in their study that a 1000 m buffer from areas of ecological value should be applied, as well as a buffer of 400 m from water bodies. In this study, inland waters (covering major watercourses and lakes), including a 400 m buffer, as well as the following ecologically significant areas, including a 1000 m buffer, were deemed unfeasible for wind farm development and hence excluded:

- National parks registered under NSW National Parks and Wildlife Services (NPWS) estate;
- Nature reserves registered under NPWS estate;
- State conservation areas and Karst conservation reserves registered under NPWS estate;
- Regional parks registered under NPWS estate;
- Protected littoral forest under NSW State Environmental Planning Policy (SEPP) 26;
- Protected wetlands under SEPP 14; and
- Protected coastline under SEPP 71.

C5. Cultural protection: In order to protect cultural heritage, Baban and Parry (2001) recognised in their study the exclusion of historical sites as well as the application of a 1000 m buffer zone. Additionally, a 1000 m buffer to archaeological and historical sites was also applied by Latinopoulos and Kechagia (2015). In this study, the following culturally significant features, including a 1000 m buffer, were deemed unfeasible for wind farm development and hence excluded:

- Aboriginal areas registered under NPWS estate;
- 'CCA Zone 2' Aboriginal areas registered under NPWS estate; and
- Places and objects of particular importance to the people of NSW, listed on the NSW State Heritage Register.

C6. Safety restrictions: For safety reasons, wind farms should not be located in close proximity to infrastructure such as road and rail network, or airports. Previous studies have applied various safety distances, with the minimum distance to roads ranging from 150 m (Latinopoulos & Kechagia, 2015; Hansen, 2005) to 500 m (Bennui, 2007), and the minimum distance from airports ranging from 3000 m (Latinopoulos & Kechagia, 2015; Bennui, 2007) and up to 5000 m (Hansen, 2005). For the purpose of this study, roads (principal, secondary and duel carriageway) and the rail network, including a buffer of 500 m, as well as airports and heliports, including a buffer of 5000 m, were deemed unfeasible for wind farm development and hence excluded.

Table 1. Summary of decision constraints applied in this study.

Constraint	Category	Criteria	Sustainability Perspective
C1	Wind speed	Wind speed ≥ 5 m/s	Economic
C2	Built-up areas	Distance from built-up areas, populated places and towns > 2000 m	Social
C3	Land use restrictions	Land use classification is RU1, RU2, RU3, RU4, IN1, IN3, SP1 or SP2	Environmental and social, legislative framework
C4	Environmental protection	Distance from ecologically significant areas > 1000 m and from inland waters > 400 m	Environmental and social
C5	Cultural protection	Distance from culturally significant features >1000 m	Social
C6	Safety restrictions	Distance from roads and rail network >500 m and from airports >5000 m	Social (Public safety)

4.1.2 Description of Decision Factors

In this study, eight decision factors (F1-F8) were identified, which are described below and summarised in Table 2.

F1. Wind speed: Decision factor F1 denotes the site suitability with respect to wind speed, based on an IFMF. The least suitable threshold value (q-value) was set to a wind speed value of 5 m/s in accordance with the associated decision constraint C1. The most suitable threshold value (p-value) was set to 7.5 m/s, a threshold value also applied by Latinopoulos and Kechagia (2015).

F2. Slope gradient: Decision factor F2 denotes the site suitability with respect to the prevailing slope gradient, based on a DFMF. The threshold value for slope gradient varies in previous scientific publications. A questionnaire targeting relevant public and private sectors in the UK found that wind farm areas must have a slope angle less than 10 percent (Baban & Parry, 2001); however, some studies have applied a higher threshold such as Latinopoulos and Kechagia (2015) who used a q-value of 20 percent for their fuzzy membership function. In this study, the q-value for slope gradient was set to 15 percent and the p-value set to 2 percent, considering both the economic feasibility (accessibility) and the minimisation of potential environmental impacts from erosion and soil loss.

F3. Land cover: Decision factor F3 denotes the site suitability with respect to the qualitative attribute of land cover. Land cover classes in NSW were classified into six groups and a six point Likert-type scale applied, ranging from zero (0) to one (1), similarly to in the study by Latinopoulos and Kechagia (2015). In this study, site suitability with respect to the prevailing land cover was evaluated based primarily on tree density, where a higher density indicates a greater environmental impact (Tegou et al., 2010), clearing costs for developers (Van Haaren & Fthenakis, 2011), as well as risks of nearby vegetation affecting the wind speed and direction of flow (Baban & Parry, 2001). Land cover classes were categorised into the following groups (listed with decreasing suitability):

- Cultivated and managed land;
- Forbs and graminoids (grasses);
- Shrubs and chenopods;
- Trees: scattered and sparse;
- Trees: open and closed; and
- Not suitable land cover.

The membership value assigned to each land cover group is detailed in Table 2. Moreover, the categorisation of 'not suitable land cover' was based on land cover classes excluded by Latinopoulos and Kechagia (2015), and included extraction sites/artificial surfaces, inland waterbodies, salt lakes, irrigated cropping, irrigated pasture, irrigated sugar, and wetlands.

F4. Proximity to transmission network: Decision factor F4 denotes site suitability with reference to the proximity to the national transmission network, based on a DFMF. Baban and Parry (2001) identified in their study that from an economic perspective wind farms must not be located further than 10 000 m away from the grid; yet, not closer than 100 m. However, due to the increasing size (capacity) of wind farms, Geoscience Australia & ABARE (2010) state that wind farm locations at a distance of up to 100 000 m from the national transmission network have been proposed in Australia. In this study, the q-value and p-value for decision factor F4 were set to 100 000 m and 100 m, respectively. It should also be noted that decision factor F4 only includes the national transmission network (sub-transmission and high-voltage distribution not incorporated) and does therefore not represent all opportunities for wind farms to connect to the electricity grid.

F5. Proximity to road network: Decision factor F5 denotes site suitability with respect to the proximity to the road network (including principal roads, secondary roads, duel carriageways and minor roads), based on a DFMF. According to Baban and Parry (2001), wind farms should not be located further than 10 000 m from roads in order to facilitate access, and minimise construction and maintenance costs. Thus, in this study the q-value for decision factor F5 was set to 10 000 m and the p-value set to 500 m (see buffer distance from roads discussed under decision constraint C6).

F6. Distance from ecologically significant areas: Decision factor F6 denotes site suitability with respect to the distance from ecologically significant areas, based on an IFMF. Considering potential negative environmental impacts, it was deemed suitable to assign a higher membership value to areas further away from ecologically significant areas. Aydin et al. (2010) considered in their study a p-value of 5000 m to be appropriate in their fuzzy set for protection of bird habitat. Hence, in this study the q-value for decision factor F6 was set to 1000 m in accordance with the buffer distance defined under decision constraint C4, and the p-value set to 5000 m. Furthermore, ecologically significant areas considered in decision factor F6 included the following:

- National parks registered under NPWS estate;
- Nature reserves registered under NPWS estate;
- State conservation areas and Karst conservation reserves registered under NPWS estate;
- Regional parks registered under NPWS estate;
- Protected littoral forest under SEPP 26;
- Protected wetlands under SEPP 14;
- Protected coastline under SEPP 71;
- Declared critical habitat under the Threatened Species Conservation Act 1995; and
- Declared critically endangered ecological communities (CEECs) under the Threatened Species Conservation Act 1995 and the Environment Protection and Biodiversity Conservation Act 1999.

F7. Distance from culturally significant features: Decision factor F7 denotes site suitability with respect to the distance from culturally significant features or areas, based on an IFMF. Considering potential negative social impacts such as noise and visual disturbances, it was deemed suitable to assign a higher membership value to areas further away from culturally significant features. In this study, control points similarly to in the study by Latinopoulos and Kechagia (2015) were deemed appropriate, with a q-value of 1000 m (see discussion on buffer distance under decision constraint C5) and a p-value of 3000 m. The following culturally significant features were considered in decision factor F7:

- Aboriginal areas registered under NPWS estate;
- CCA Zone 2 Aboriginal areas registered under NPWS estate; and
- Places and objects of particular importance to the people of NSW, listed on the NSW State Heritage Register.

F8. Strategic agricultural land: Decision factor F8 denotes site suitability with respect to the qualitative attribute of strategic agricultural land, based on a binary scoring system. Wind farms are compatible with agricultural activities such as cropping and grazing (Australian Greenhouse Office & Australian Wind Energy Association, 2004); however, Baban and Parry (2001) identified in their study that wind farm developments should avoid high value agricultural land. Therefore, strategic agricultural land, which is land with valuable natural resource characteristics and/or socio-economic value, was deemed not suitable for wind farm development and hence assigned a membership value equal to zero (0); whilst all other areas were deemed ideal and subsequently assigned a membership value equal to one (1).

Table 2. Summary of decision factors applied in this study.

Factor	Category	MF type / Value	Unit	q-value	p-value	Sustainability Perspective
F1	Wind speed	IFMF	m/s	5	7.5	Economic and environmental
F2	Slope gradient	DFMF	%	15	2	Economic and environmental
F3	Land cover (qualitative variable)	N/A	-	-	-	Economic and environmental
	- Cultivated and managed land	1	-	-	-	
	- Forbs and graminoids	0.8	-	-	-	
	- Shrubs and chenopods	0.6	-	-	-	
	- Trees: scattered/sparse	0.4	-	-	-	
	- Trees: open/closed	0.2	-	-	-	
	- Not suitable land cover	0	-	-	-	
F4	Proximity to transmission network	DFMF	m	100 000	100	Economic
F5	Proximity to road network	DFMF	m	10 000	500	Economic
F6	Distance from ecologically significant areas	IFMF	m	1000	5000	Environmental and social
F7	Distance from culturally significant features	IFMF	m	1000	3000	Social
F8	Strategic agricultural land (qualitative variable)	N/A	-	-	-	Environmental, social and economic
	- Not strategic agricultural land	1	-	-	-	
	- Strategic agricultural land	0	-	-	-	

4.2 Data Collection and Pre-Processing

Data was obtained to cover economic, social and environmental aspects of wind farm site suitability. Collected datasets were publically available and primarily obtained from Geoscience Australia's 'Data and Publications Search' catalogue, the NSW Department of Planning & Environment's 'Open Data' portal and the NSW Office of Environment & Heritage's 'Spatial Data Online Access' portal. Most datasets were acquired in vector format; however, data on elevation, land cover and wind speed were obtained in raster format. Datasets used in this study are summarised in Table 3.

Table 3. Summary of datasets used in this study.

Dataset Description	Reference
Administrative boundaries	Australian Bureau of Statistics (2011)
Airports (including heliports)	Geoscience Australia (2006)
Built-up areas (incl. populated places and towns)	Geoscience Australia (2006); Wade et al. (2016)
Critically endangered ecological communities	Office of Environment & Heritage (2015a)
Critical habitat	Office of Environment & Heritage (2010)
Elevation	Geoscience Australia (2010)
Inland water (major watercourses and lakes)	Geoscience Australia (2006)
Land cover	Lymburner et al. (2010)
Land use zoning	Department of Planning & Environment (n.d.)
National Parks and Wildlife Service estate	Office of Environment & Heritage (2015b)
Road and railway network	Geoscience Australia (2006)
State Environmental Planning Policy 14	Department of Planning & Environment (n.d.)
State Environmental Planning Policy 26	Department of Planning & Environment (n.d.)
State Environmental Planning Policy 71	Department of Planning & Environment (n.d.)
Strategic agricultural land - Biophysical	Department of Planning & Environment (n.d.)
Strategic agricultural land - Equine	Department of Planning & Environment (n.d.)
Strategic agricultural land - Viticulture	Department of Planning & Environment (n.d.)
State heritage register	Office of Environment & Heritage (2015c)
Transmission network	Wade et al. (2016)
Wind farm locations (existing)	Wade et al. (2016)
Wind speed at 100 m	Wade et al. (2016)

Data on wind speed at a height of 100 m above ground level and with a spatial resolution of 1 km was obtained from the '*Renewable Energy Map of New South Wales Version 1*' dataset published by the government organisation Geological Survey NSW (Wade et al., 2016). This wind speed raster layer was generated using the WAsP model and based on a microscale wind speed map across NSW produced by Garrad Hassan Pacific Pty Ltd (trading as DNV GL). The microscale wind speed map was in turn derived from the previously generated mesoscale modelling by DNV GL, covering the whole of Australia with a horizontal resolution of approximately 5 km. The mesoscale modelling was based on a 10-year simulation of local and regional wind flows, using the DNV GL wind mapping system, which primarily incorporates two key technologies: the state-of-the-art community mesoscale model called 'weather research and forecasting model'; and an ensemble downscaling technique based on a method called 'analog ensemble method'. Furthermore, it should be noted that wind speed values are derived from modelling output only and have not been validated towards observations (Wade et al., 2016).

Land cover data was obtained from the dataset '*Dynamic Land Cover Dataset of Australia*' by Lymburner et al. (2010), which conforms to the 2007 International Standards Organisation (ISO) land cover standard (19144-2) and comprises 34 ISO land cover classes in Australia. The source data for the dataset is a time series of enhanced vegetation index data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites, operated by National Aeronautics and Space Administration (NASA), which includes 186 snapshots of vegetation greenness across Australia from year 2000 to 2008, with a spatial resolution of 250 m.

Data on built-up areas was based on three feature types obtained from two datasets: 'built-up areas' defined as areas where buildings are close together, with associated road and other infrastructure networks (minimum size criteria of 390 625 m^2), and 'populated places' (named settlement with a population of 200 or more) outlined in the '*GEODATA TOPO 250K Series 3*' dataset published by Geoscience Australia (2006); and 'towns' as detailed in the '*Renewable Energy Map of New South Wales Version 1*' dataset published by Wade et al. (2016).

Transmission network data was obtained from the '*Renewable Energy Map of New South Wales Version 1*' dataset, which details the national electricity transmission lines (66 kV and greater) in NSW. Transmission lines are in the dataset referred to as a network of wires and insulators used to connect and transport high voltage electricity from generators to large demand customers and the lower voltage electricity distribution network (Wade et al., 2016). It should further be noted that the transmission network data applied in this study does not include the sub-transmission network.

Pre-processing of datasets applied in this study was performed using 'ArcGIS 10.2.2 for Desktop Advanced' software developed by Esri and included: projection to the geographic coordinate system 'Geocentric Datum of Australia (GDA) 1994' (Spatial Services, 2016a); selection of records based on attribute queries; distance calculations and creation of geodesic buffers; and clip, union and dissolve geoprocessing. Following the calculation of geodesic buffers, all datasets were projected to the projected coordinate system 'GDA 1994 NSW Lambert', which is suitable for state-wide GIS data (Spatial Services, 2016b). Pre-processing also included conversion of vector data to raster (grid cell) data and resampling to a cell size of 150 x 150 m using nearest or bilinear resampling techniques. Before conversion to raster format, the geometry of vector data was checked and any identified geometry problems repaired using the ArcGIS Data Management toolbox.

Slope gradient calculations were derived from the '*1 second SRTM Derived Smoothed Digital Elevation Model (DEM-S) version 1.0*' dataset published by Geoscience Australia (2010), with a resolution of approximately 30 m. The slope gradient was calculated based on the percent rise measurement, which can be expressed as the tangent of the angle of inclination multiplied by 100. Furthermore, due to the geoprocessing performance, the polygon dataset of CEECs was first generalised by aggregating polygons prior to creating buffers. The non-orthogonal method was used with an aggregation distance set to 1000 m.

4.3 GIS Analysis

The general GIS work flow and analysis methodology conducted in this study is illustrated in Figure 5 and described in more detail in the following sections. The GIS analysis was performed using 'ArcGIS 10.2.2 for Desktop Advanced' software developed by Esri.

Figure 5. General GIS work flow and methodology of this study.

4.3.1 Decision Constraints Analysis

Individual constraint layers were created for each decision constraint using the 'Reclassify' or 'Raster Calculator' tool in the ArcGIS Spatial Analyst toolbox. Unfeasible areas were assigned a value of zero (0) and all other areas a value of one (1).

A composite constraint layer was then created using 'Raster Calculator', where all individual constraint layers were multiplied in order to identify areas classified as feasible considering all constraint criteria. Hence, the resulting composite constraint layer details exclusion zones (unfeasible areas) assigned a value of zero (0), as well as potential development sites (feasible areas) assigned a value of one (1).

4.3.2 Standardisation of Decision Factors

Decision factors were primarily standardised by application of the fuzzy sets theory and the 'Fuzzy Membership' overlay tool in the ArcGIS Spatial Analyst toolbox. A standardised map layer was created for each respective decision factor, detailing the grade of membership ranging between zero (0: not satisfied) and one (1: fully satisfied). As such, a membership grade or value of zero (0) represents a not suitable location (grid cell) and a value of one (1) an ideal location. Prior to the standardisation of decision factors F4 (proximity to transmission network), F5 (proximity to road network), F6 (distance from ecologically significant areas) and F7 (distance from culturally significant features), the Euclidean distance was calculated using the 'Euclidean Distance' tool located in the ArcGIS Spatial Analyst toolbox.

Furthermore, decision factor F3 (land cover) was standardised by first assigning membership values to land cover classes in the attribute table, followed by using the 'Lookup' tool in the ArcGIS Spatial Analyst toolbox. Decision factor F8 (strategic agricultural land) was standardised by reclassification using the 'Reclassify' tool located in the ArcGIS Spatial Analyst toolbox.

4.3.3 Multi-Criteria Decision Analysis and Compilation of Suitability Index

A decision rule can be described as a procedure or method for evaluating a set of decision alternatives, and the weighted linear combination (WLC) technique is one of the most commonly used decision rules in GIS-based MCDA. This technique can be summarised as a map combination procedure where each evaluation criterion (standardised factor) is multiplied by a weight and the results summed to produce a composite map (Malczewski& Rinner, 2015).

In the context of this study, the WLC technique was used to compile an overall suitability index (SI) where each raster grid cell denotes a composite degree of wind farm site suitability. Standardised decision factors were first combined using the 'Weighted Sum' overlay tool in the ArcGIS Spatial Analyst toolbox and by implementing the decision rule described in Equation 3, where *SI* is the suitability index score for cell *j*, w_i is the weight for factor *i* (*i* = 1,….8) and $x_{i,j}$ is the standardised fuzzy membership value of cell *j* for factor *i*.

$$SI_j = \sum_{i=1}^{n} w_i x_{i,j} \qquad \text{Equation 3}$$

Following the combination of decision factors, exclusion zones (unfeasible areas) identified in the decision constraint analysis were incorporated by multiplying the final suitability index with the composite constraint map, using the 'Raster Calculator' tool located in the ArcGIS Spatial Analyst toolbox.

Furthermore, the relative importance (weight) of decision factors was in this study based on the author's knowledge and subjective judgments, and by trying to depict three policy scenarios:

1. Equal weights;
2. Environmental/social priority; and
3. Economic priority.

Concerning Scenario 1, decision factors (F1-F8) were assumed to be of equal importance and thus equally assigned a weight of 0.125 (1/8). However, in Scenarios 2 and 3 weights were derived by application of the analytic hierarchy process (AHP). The Department for Communities and Local Government (2009) states that AHP is a commonly applied method in multi-criteria analysis, and its ability to convert subjective assessments to a set of overall weights was deemed appropriate for this study. Pohekar and Ramachandran (2004) also identified in their literature review that the AHP method is the most popular technique for MCDA in sustainable energy planning.

The AHP is a general theory of measurement and a process which generally consists of three underlying concepts: structuring the decision problem as a hierarchy of goals; defining criteria and alternatives; and pair-wise comparisons of the hierarchy elements at each level, as well as in respect to the level above, followed by vertical synthesising of judgements to produce a set of overall priorities for the hierarchy of goals. As such, the AHP attempts to estimate in numerical terms the relative ability of the alternatives to achieve the overall goal (Saaty, 1987). However, in this study, AHP was only applied to obtain weights for decision factors based on pairwise comparisons.

Pairwise comparisons were based on a nine-point continuous scale (see Table 4) and results were recorded in a matrix in accordance with Saaty (1987). Weights were derived by calculating the eigenvectors using the open source software 'PriEsT – Priority Estimation Tool (AHP)' (Siraj et al., 2015). The AHP also provides a mathematical measure to determine inconsistency of judgments by calculating a consistency ratio (CR), where a CR value below 0.1 is considered acceptable (Saaty, 1987).

Table 4. The fundamental scale for pairwise comparisons (Saaty, 1987).

Intensity of Importance on an Absolute Scale	**Definition**
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent judgements
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, the *j* has the reciprocal value when compared with *i*

Matrices of pairwise comparisons and associated weights for Scenarios 2 and 3 are presented in Table 5 and Table 6. Moreover, pairwise judgments were deemed to be consistent with a CR value of 0.013 in both investigated scenarios. Decision factor weights for the three policy scenarios are also summarised in Table 7.

Table 5. Matrix of applied pairwise comparisons and weights of factors for Scenario 2.

	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**Weight**
F1	-	3	1/3	3	3	1/5	1/5	1/3	0.062
F2	1/3	-	1/5	1	1	1/9	1/9	1/5	0.027
F3	3	5	-	5	5	1/3	1/3	1	0.130
F4	1/3	1	1/5	-	1	1/9	1/9	1/5	0.027
F5	1/3	1	1/5	1	-	1/9	1/9	1/5	0.027
F6	5	9	3	9	9	-	1	3	0.298
F7	5	9	3	9	9	1	-	3	0.298
F8	3	5	1	5	5	1/3	1/3	-	0.130

Table 6. Matrix of applied pairwise comparisons and weights of factors for Scenario 3.

	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**	**Weight**
F1	-	4	6	4	6	9	9	9	0.426
F2	1/4	-	3	1	3	6	6	6	0.175
F3	1/6	1/3	-	1/3	1	2	2	2	0.063
F4	1/4	1	3	-	3	6	6	6	0.175
F5	1/6	1/3	1	1/3	-	2	2	2	0.063
F6	1/9	1/6	1/2	1/6	1/2	-	1	1	0.033
F7	1/9	1/6	1/2	1/6	1/2	1	-	1	0.033
F8	1/9	1/6	1/2	1/6	1/2	1	1	-	0.033

Table 7. Summary of decision factor weights for investigated policy scenarios.

Decision Factor	**Scenario 1 Equal Weights**	**Scenario 2 Environmental Priority**	**Scenario 3 Economic Priority**
F1 - Wind speed	0.125	0.062	0.426
F2 - Slope gradient	0.125	0.027	0.175
F3 - Land cover	0.125	0.130	0.063
F4 - Proximity to transmission network	0.125	0.027	0.175
F5 - Proximity to road network	0.125	0.027	0.063
F6 - Distance from ecologically significant areas	0.125	0.298	0.033
F7 - Distance from culturally significant features	0.125	0.298	0.033
F8 - Strategic agricultural land	0.125	0.130	0.033

Additionally, for the purpose of statistical analysis, the suitability index for each policy scenario was reclassified in accordance with the suitability classes presented in Table 8, using the 'Reclassify' tool located in the ArcGIS Spatial Analyst toolbox. Following reclassification, the total area of land in NSW classified as having 'high suitability' (SI > 0.75), as well as 'moderate suitability' (0.50 < SI ≤ 0.75), within each policy scenario was calculated using the 'Tabulate Area' tool located in the ArcGIS Spatial Analyst toolbox. Furthermore, the area deemed 'acceptable' for wind farm development was defined with reference to the lower SI score of the 'moderate suitability' class and hence described with the following suitability index score interval: 0.50 < SI ≤ 1.

Table 8. Wind farm suitability classification description.

Suitability Class	**Description**
0: not suitable	SI = 0
1: low suitability	0 < SI ≤ 0.50
2: moderate suitability	0.50 < SI ≤ 0.75
3: high suitability	0.75 < SI ≤ 1

In order to assess wind farm site suitability from an economic perspective and in consideration of the 'greater' electricity network; an additional scenario was assessed, which incorporated the Essential Energy owned sub-transmission (66 kV and greater) and high voltage distribution network data, submitted in an email on 19 September 2016 by Mr Chislett. The suitability index, titled Scenario 3b, was only produced for Scenario 3 (economic priority) and was not included in the assessment of priority areas and most suitable locations. Moreover, it should be noted that the Essential Energy owned sub-transmission and high voltage distribution network data was incorporated into decision factor F4 (proximity to transmission network), and in the context of fuzzy membership calculations, the q-value was here set to 10 000 m and the p-value kept to 100 m. It was deemed appropriate to apply a lower q-value compared to the q-value of 100 000 m initially used under F4 (proximity to transmission network), since Baban and Parry

(2001) argued a maximum distance of 10 000 m from the grid. Additionally, it was considered uncertain whether the high-voltage distribution network could provide a feasible grid connection point for wind farms at a distance of 100 000 m. It should also be noted that the Ausgrid and Endeavour Energy network data was not included in the analysis.

4.3.4 Identification of Priority Areas

In order to identify *priority areas*, defined in this study as areas of particular interest for further investigation, statistics were calculated for each LGA (including unincorporated NSW) using the 'Tabulate Area' tool located in the ArcGIS Spatial Analyst toolbox. The ten LGAs with the highest percentage of land classified as 'high suitability' (SI > 0.75), in relation to their total administrative area, were nominated as priority areas within each respective policy scenario. Priority areas were deemed to be of particular interest for further investigation due to the high concentration of land deemed to be of 'high suitability', which may represent an increased probability to identify suitable wind farm locations in the real-world context.

4.3.5 Identification of Most Suitable Locations

For the purpose of identifying the *most suitable locations*, each suitability index was first resampled to a cell size of 2250 m x 2250 m using the 'Resample' tool located in the ArcGIS Data Management toolbox. The resampling cell size was chosen to reflect the minimum land area required for wind farm development (5 km^2) with reference to Nelson (2013). Following resampling, raster data was converted to point data using the 'Raster to Point' tool located in the ArcGIS Conversion toolbox and the ten points with the highest suitability index score were nominated as the most suitable locations.

4.3.6 Assessment of Existing Wind Farm Locations

The suitability index score of existing wind farm locations for each policy scenario was assessed using the 'Extract Multi Values to Points' tool located in the ArcGIS Spatial Analyst toolbox.

5. Results

5.1 Decision Constraints Analysis

Individual constraint layers are presented in Figure 6 to Figure 11, detailing exclusion zones (unfeasible areas) denoted a value equal to zero (0) and potential development sites (feasible areas) denoted a value equal to one (1). The composite constraint layer is presented in Figure 12. In addition, the total area of exclusion zones relating to each decision constraint, as well as the composite constraint layer, is presented in Table 9. As can be interpreted from Table 9, the dominant constraint factor is C4 (environmental protection), followed by C3 (land use restrictions).

Table 9. Area (km^2) of exclusion zones according to established decision constraints.

Decision Constraint	**Area of Exclusion Zones (km^2)**	**Approximate Percent of Total Study Area (%)**
C1 – Wind speed	32 248	4.0
C2 – Built-up area	16 812	2.1
C3 – Land use restrictions	87 283	10.9
C4 – Environmental protection	154 294	19.3
C5 – Cultural protection	13 903	1.7
C6 – Safety restrictions	42 929	5.4
Composite constraint	221 157	27.6

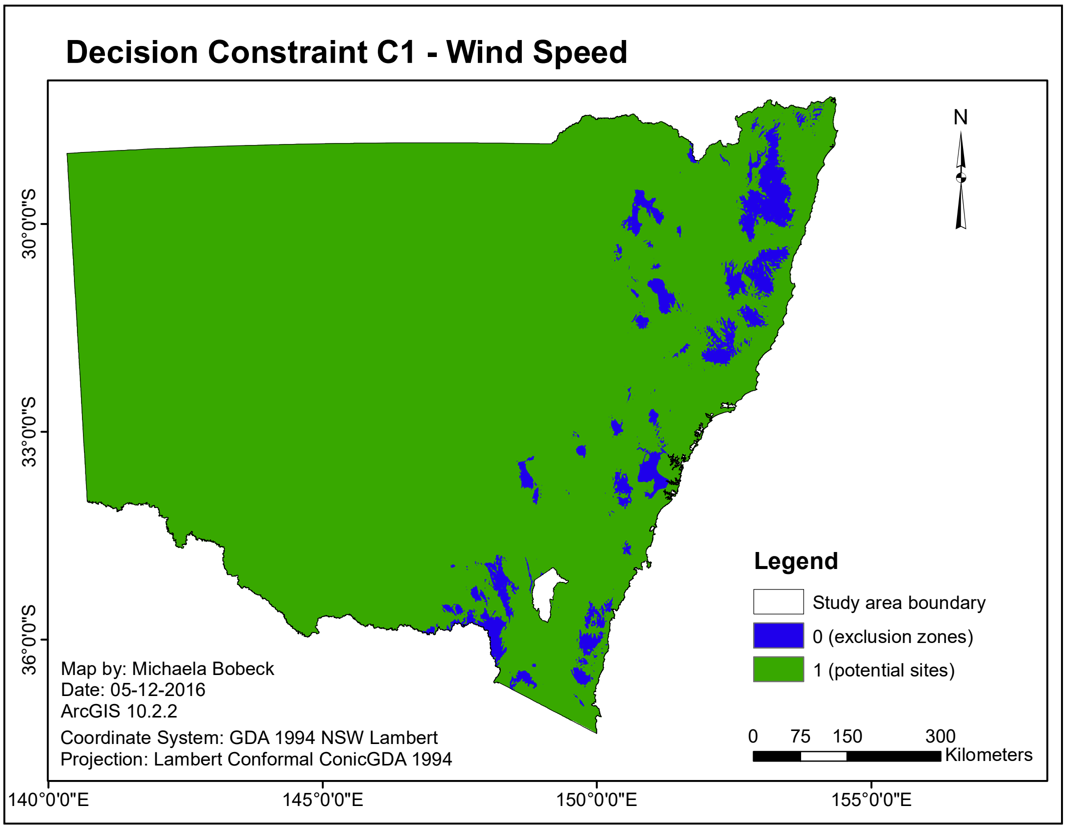

Figure 6. Potential sites based on decision constraint C1 (wind speed).

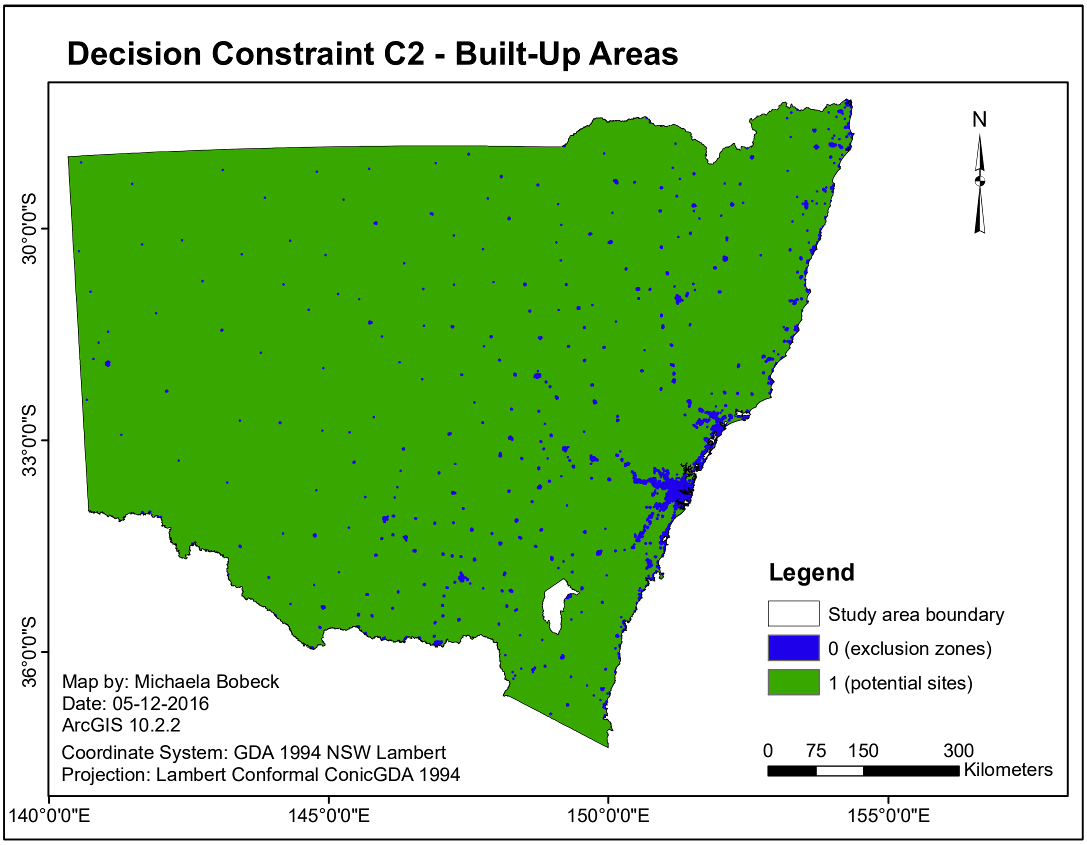

Figure 7. Potential sites based on decision constraint C2 (built-up areas).

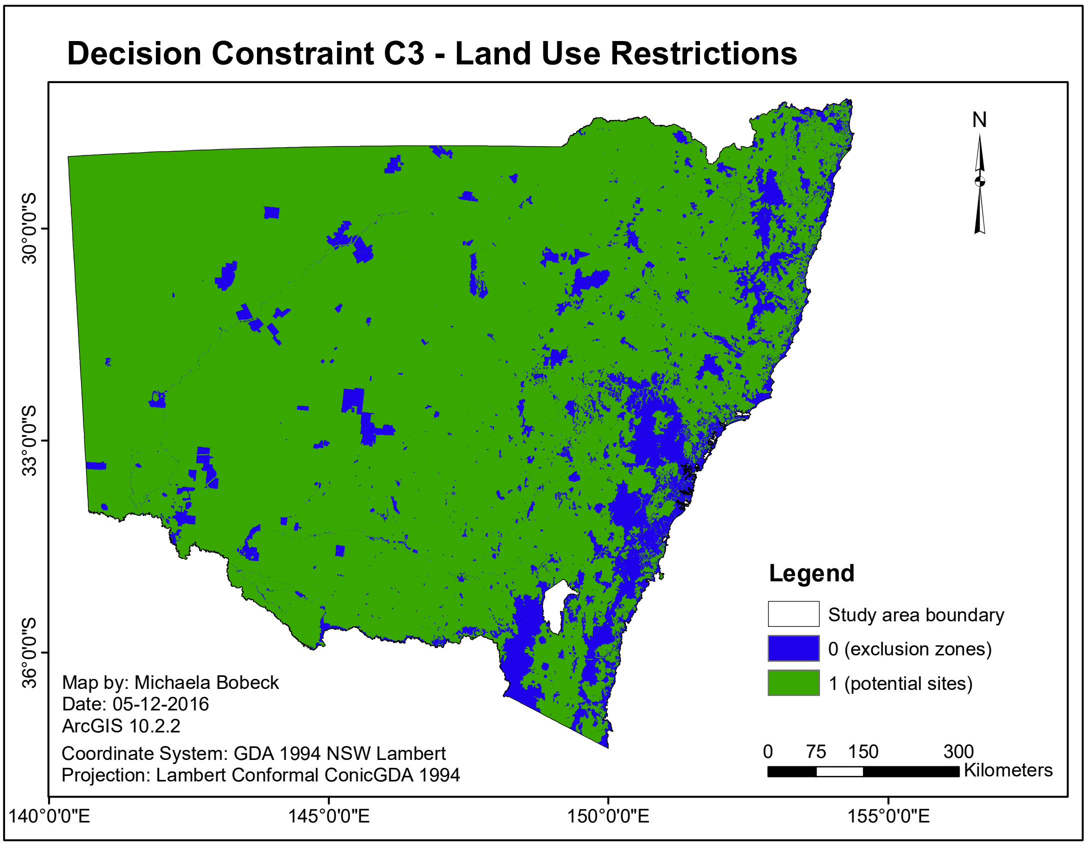

Figure 8. Potential sites based on decision constraint C3 (land use restrictions).

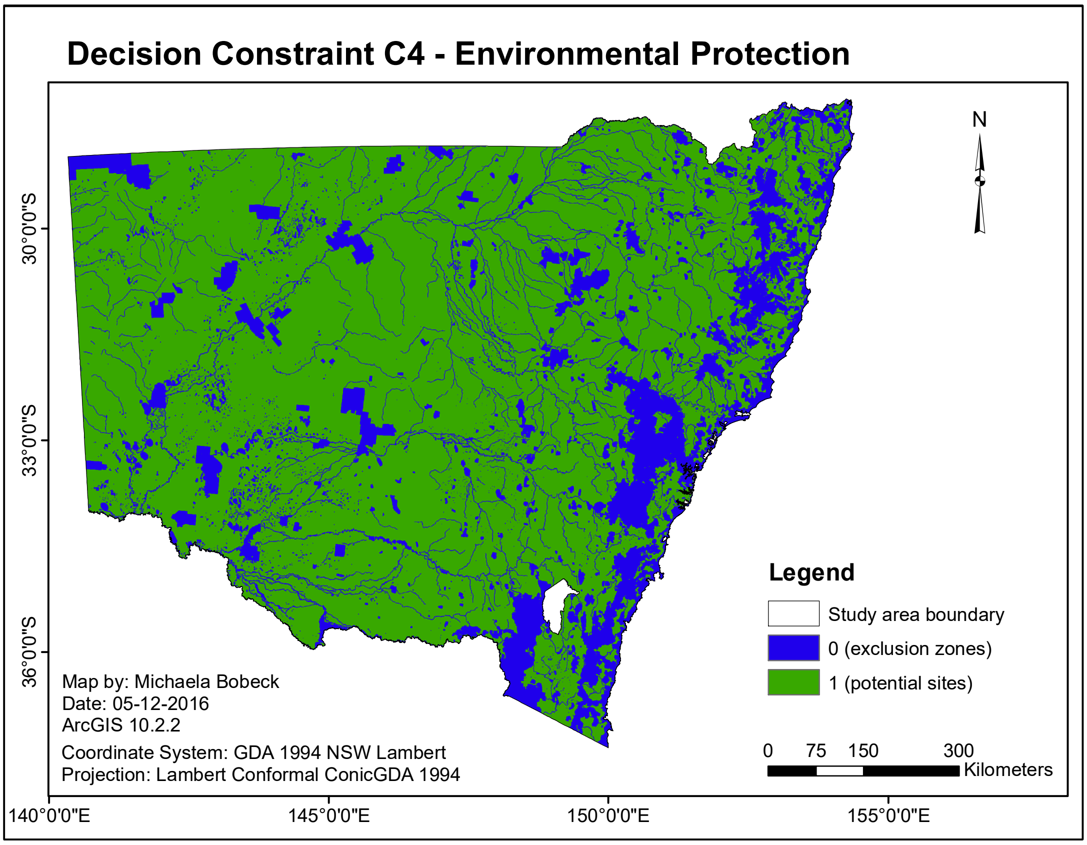

Figure 9. Potential sites based on decision constraint C4 (environmental protection).

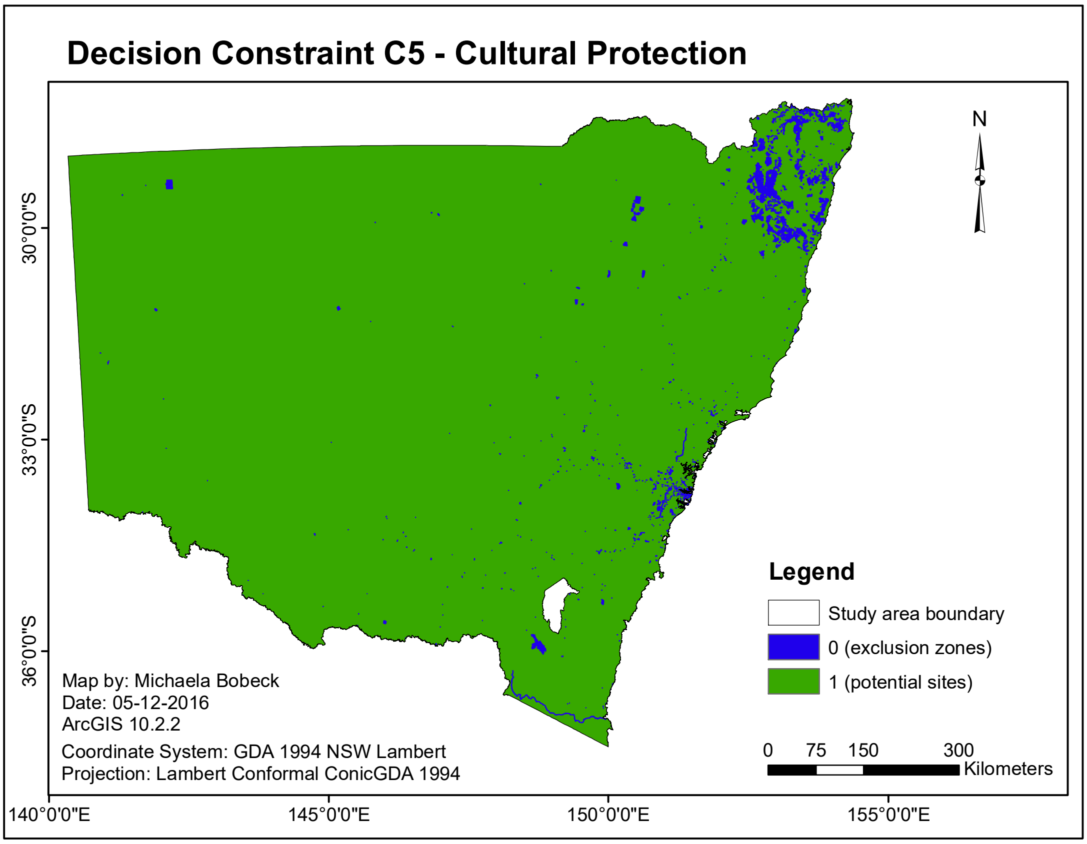

Figure 10. Potential sites based on decision constraint C5 (cultural protection).

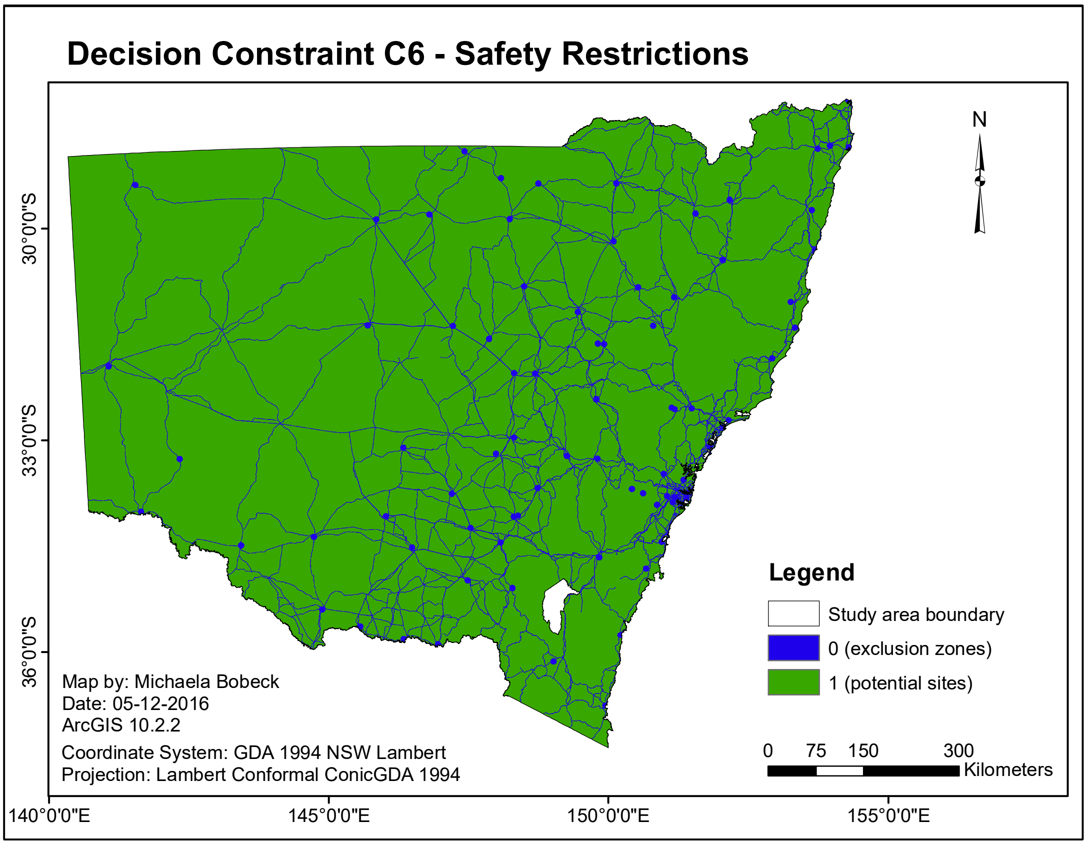

Figure 11. Potential sites based on decision constraint C6 (safety restrictions).

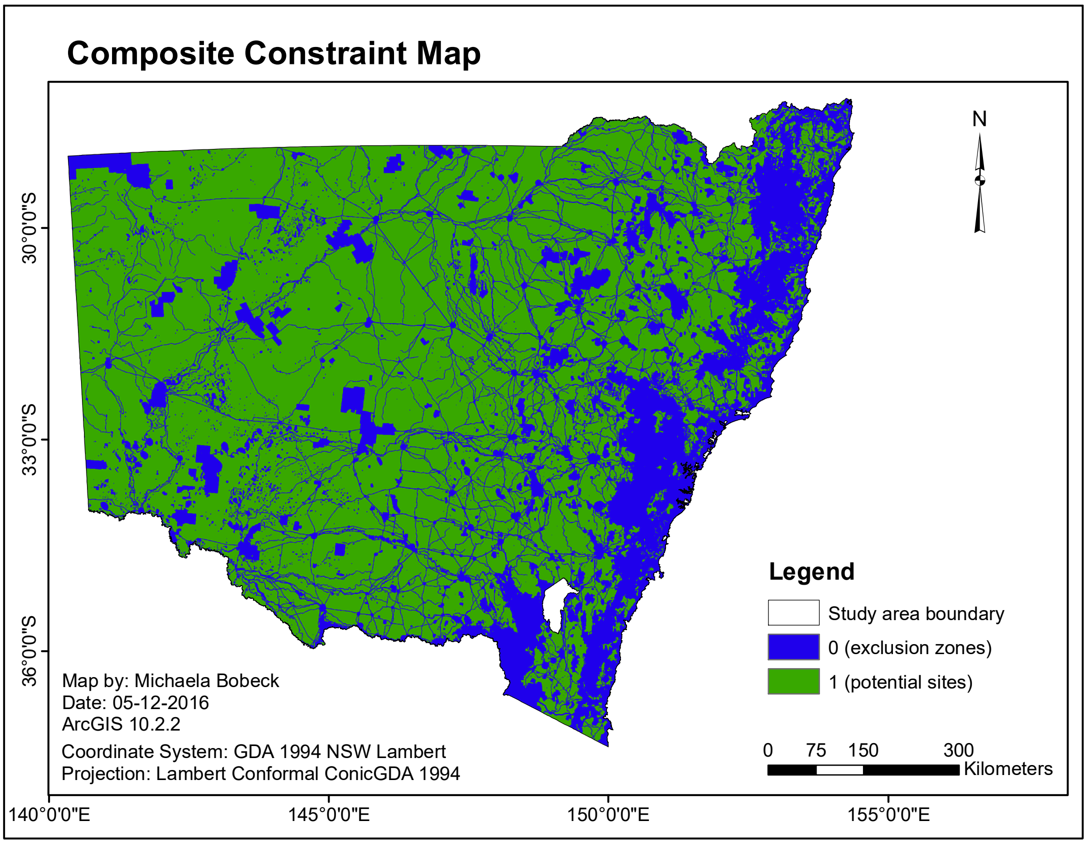

Figure 12. Composite constraint map indicating potential development sites.

5.2 Standardisation of Decision Factors

Standardised decision factors are presented in Figure 13 to Figure 20. Visual assessment of the results indicates rather large areas of moderate to high suitability (yellow and red shades); however, decision factors F3 (land cover) and F4 (proximity to transmission network) appear to involve a larger extent of lower suitability (blue shades). By considering the mean value of each decision factor raster layer detailed in Table 10, it is similarly noticeable that decision factors F4 (proximity to transmission network) and F3 (land cover), as well as F1 (wind speed), in general represent a larger extent of 'lower' membership values across NSW, compared to the other decision factors established in this study.

Table 10. Mean membership value of decision factor raster layers.

Decision Factor	Mean Membership Value
F1 – Wind speed	0.598
F2 – Slope gradient	0.801
F3 – Land cover	0.598
F4 – Proximity to transmission network	0.448
F5 – Proximity to road network	0.711
F6 – Distance from ecologically significant areas	0.786
F7 – Distance from culturally significant features	0.974
F8 – Strategic agricultural land	0.962

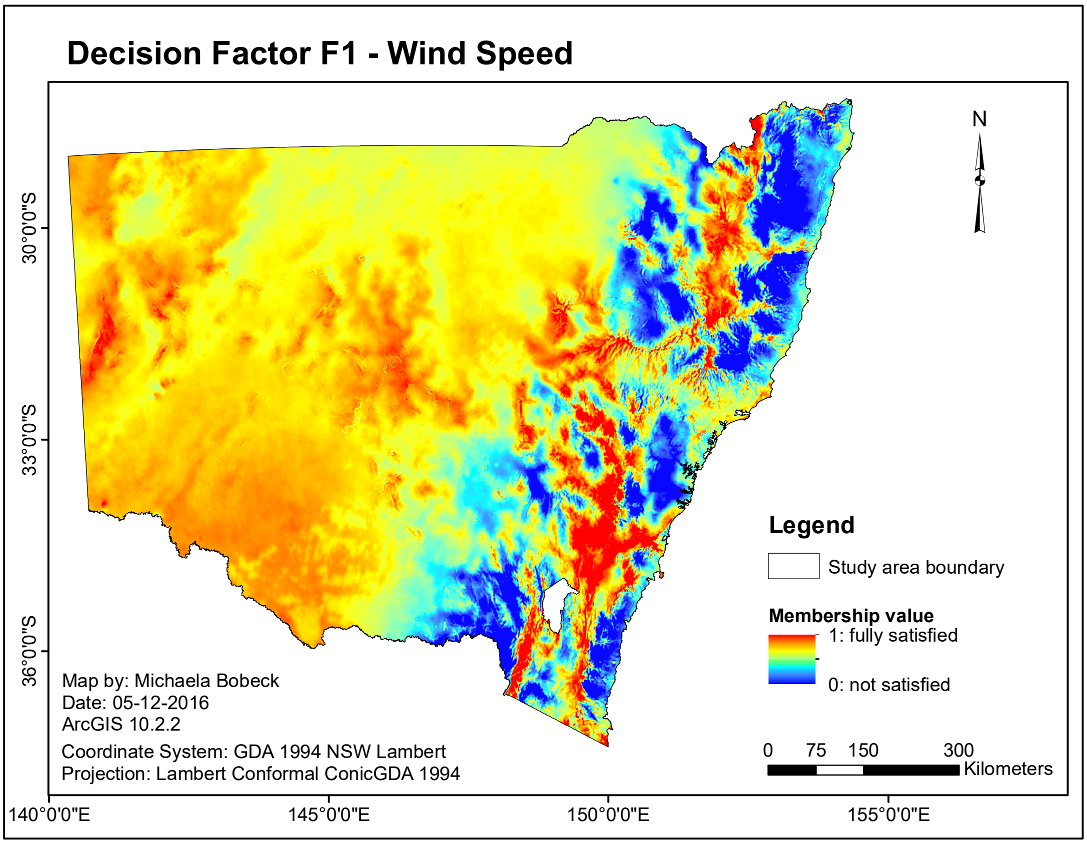

Figure 13. Standardised decision factor F1 (wind speed).

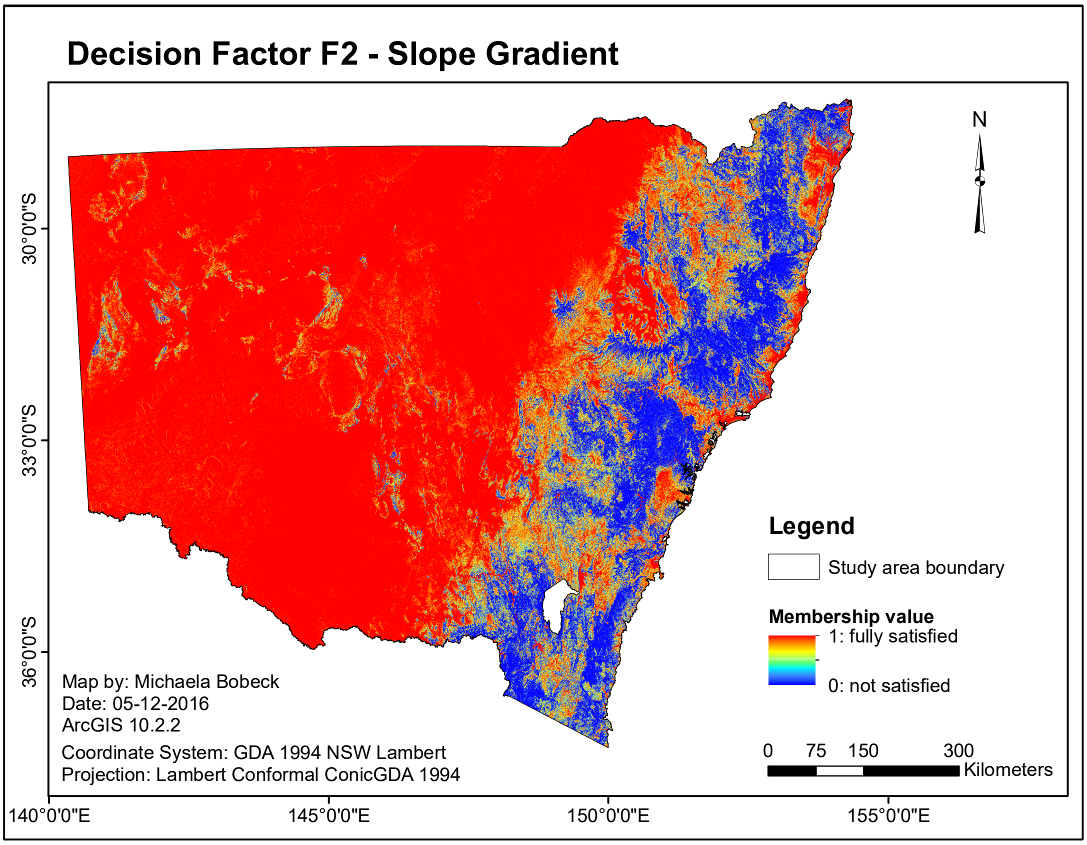

Figure 14. Standardised decision factor F2 (slope gradient).

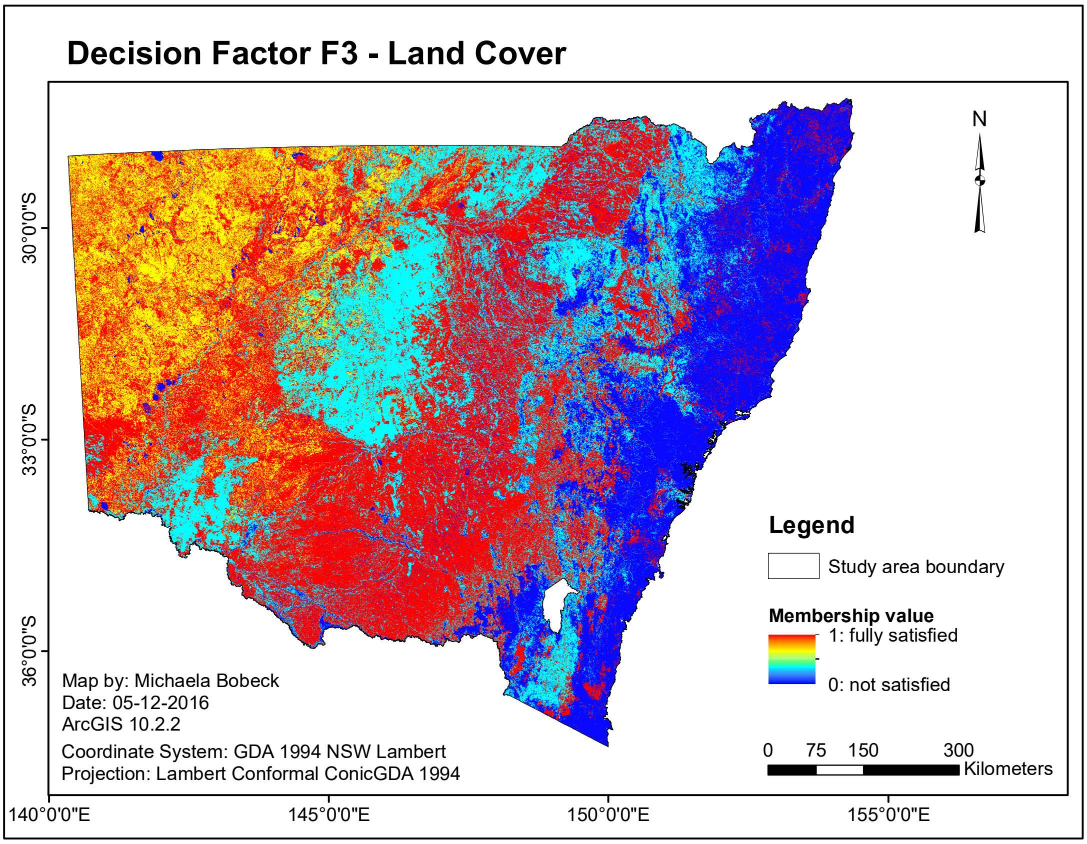

Figure 15. Standardised decision factor F3 (land cover).

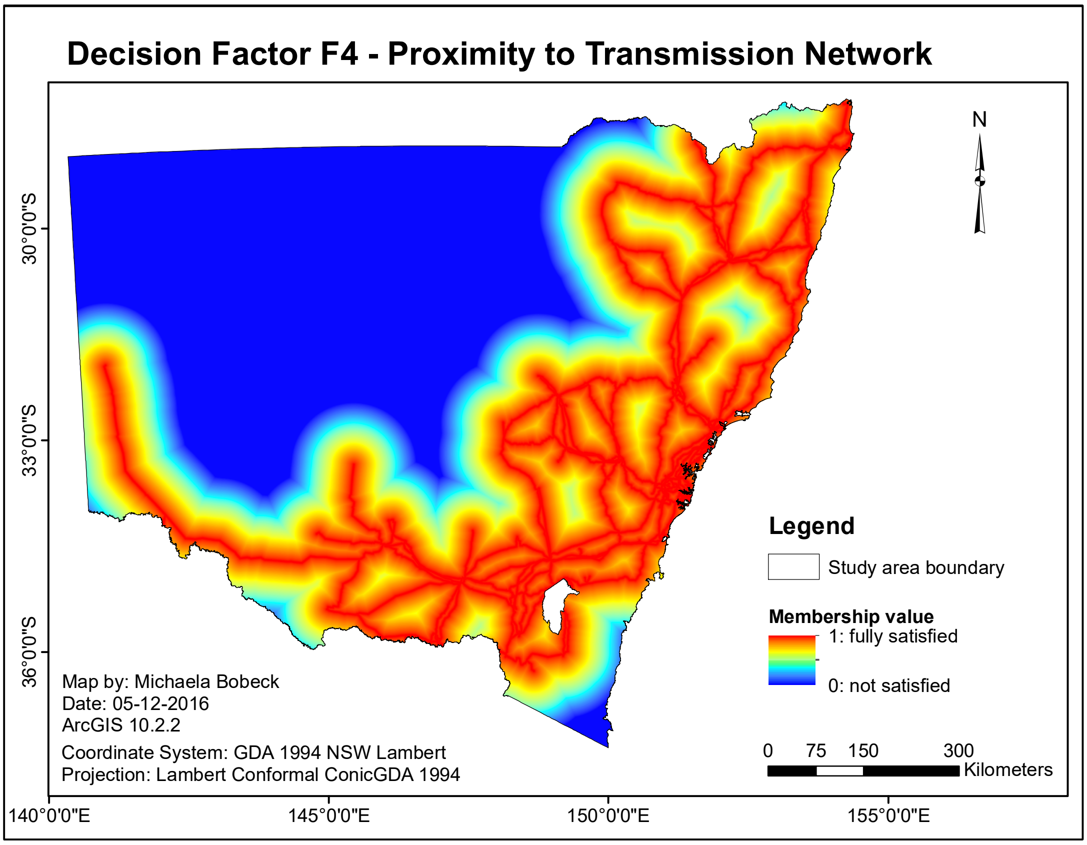

Figure 16. Standardised decision factor F4 (transmission network).

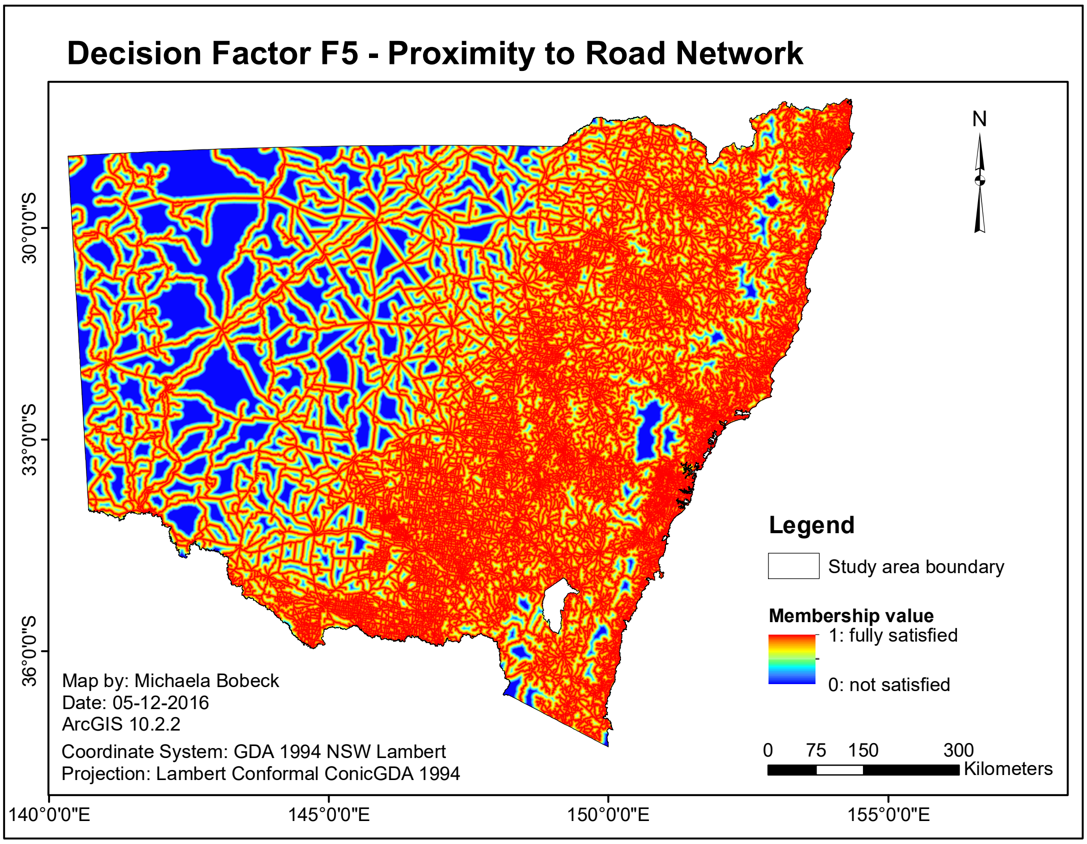

Figure 17. Standardised decision factor F5 (road network).

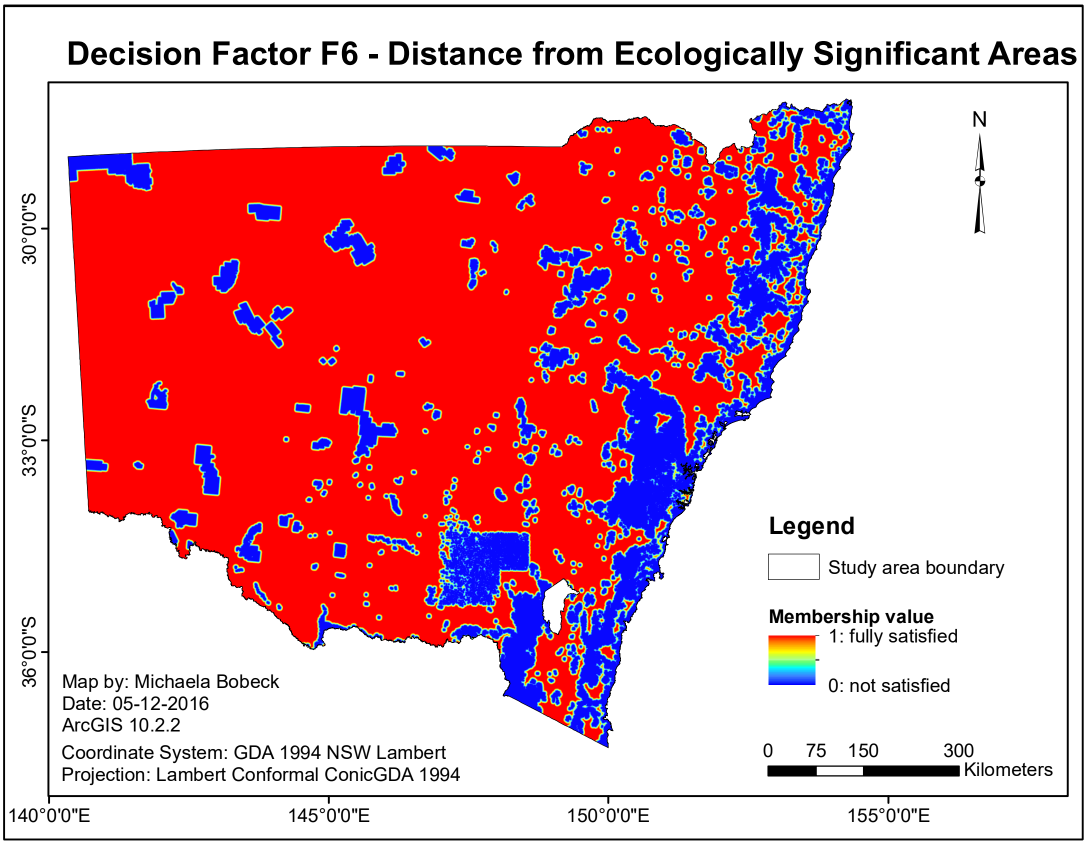

Figure 18. Standardised decision factor F6 (ecologically significant areas).

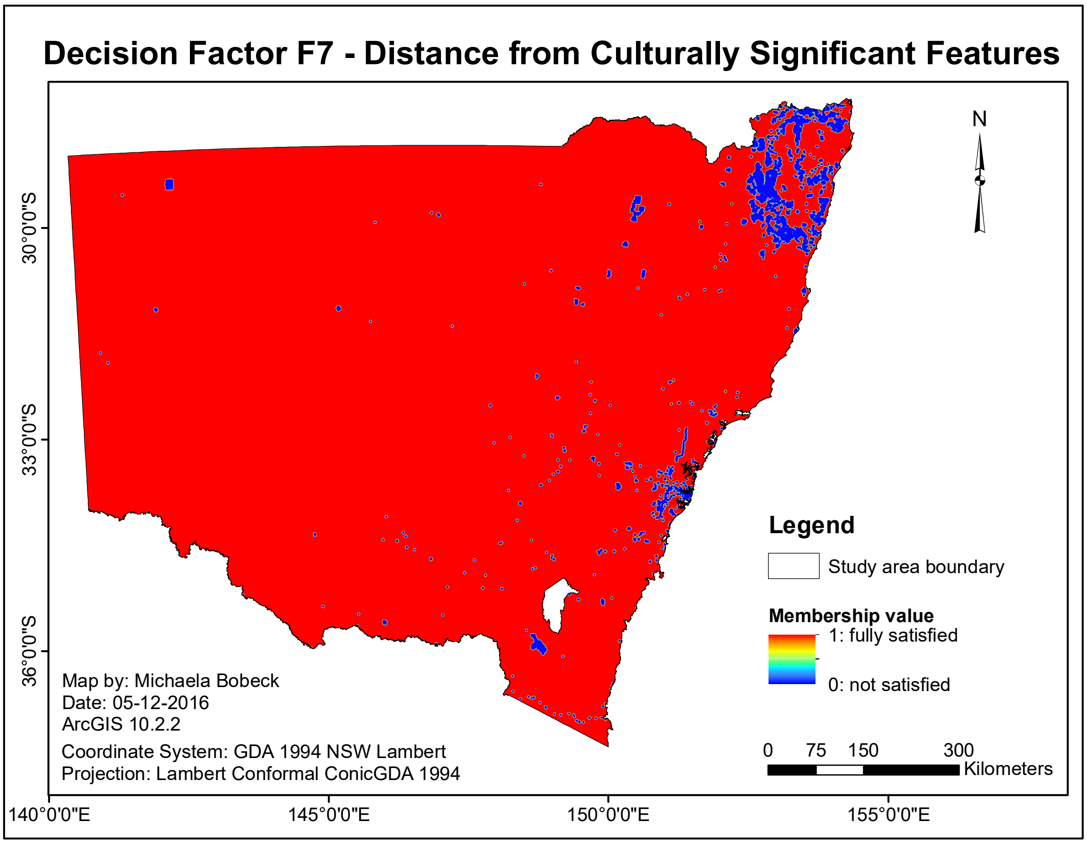

Figure 19. Standardised decision factor F7 (culturally significant features).

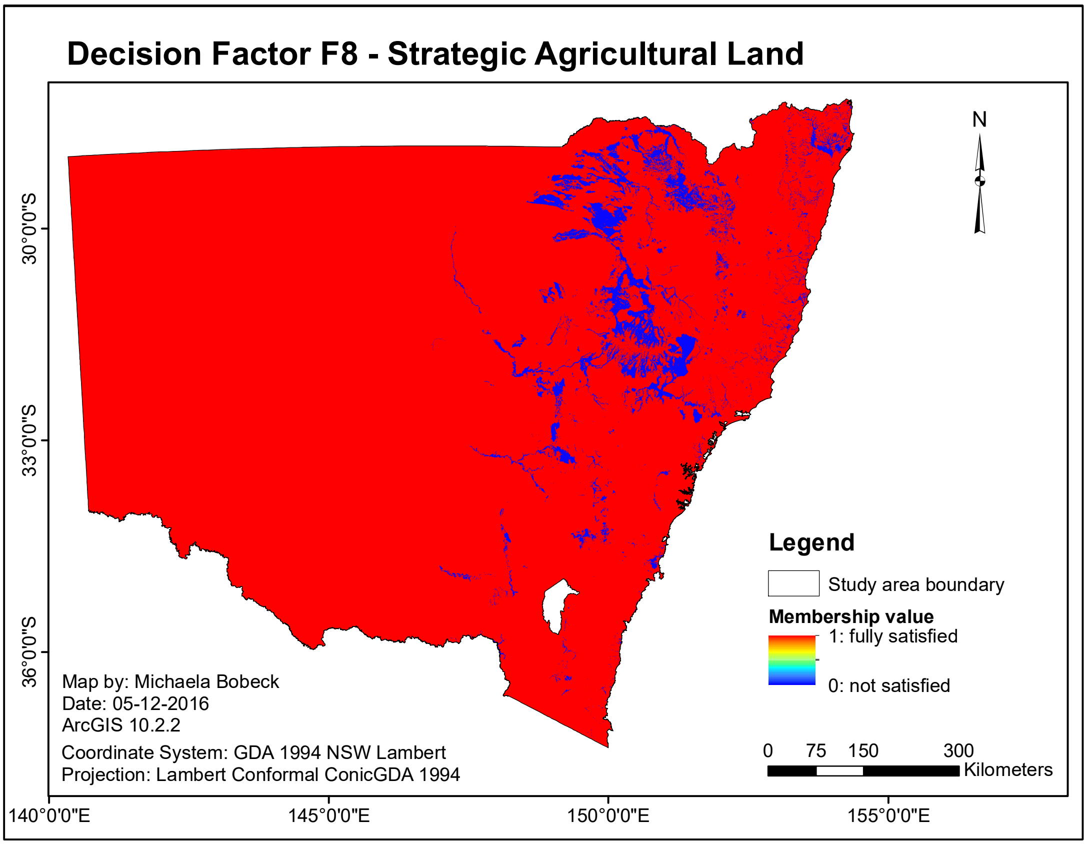

Figure 20. Standardised decision factor F8 (strategic agricultural land).

5.3 Suitability Index for Respective Policy Scenario

Figure 21 to Figure 24 present the final suitability index of the GIS-based MCDA for respective policy scenario. The maps present a varying site suitability for wind farms, with composite suitability values ranging between zero (0), not suitable locations, and one (1), ideal locations. The mean value of the produced SI raster layers is 0.55 for Scenario 1; 0.63 for Scenario 2; 0.49 for Scenario 3; and 0.52 for Scenario 3b. The total area of 'high suitability' (SI > 0.75) and 'moderate suitability' (0.50 < SI ≤ 0.75), as well as the overall area deemed 'acceptable' for wind farm development (0.50 < SI ≤ 1) within the study area, and for each policy scenario, is presented in Table 11.

Table 11. Suitability statistics for reclassified SI maps.

Policy Scenario	Area of 'High Suitability' (km^2)	Area of 'Moderate Suitability' (km^2)	Total Area Deemed 'Acceptable' (km^2)
1 – Equal weights	320 213	257 309	577 522
2 – Environmental/social priority	522 888	54 456	577 344
3 – Economic priority	121 134	432 690	553 824
3b – Economic priority	255 508	297 889	553 397

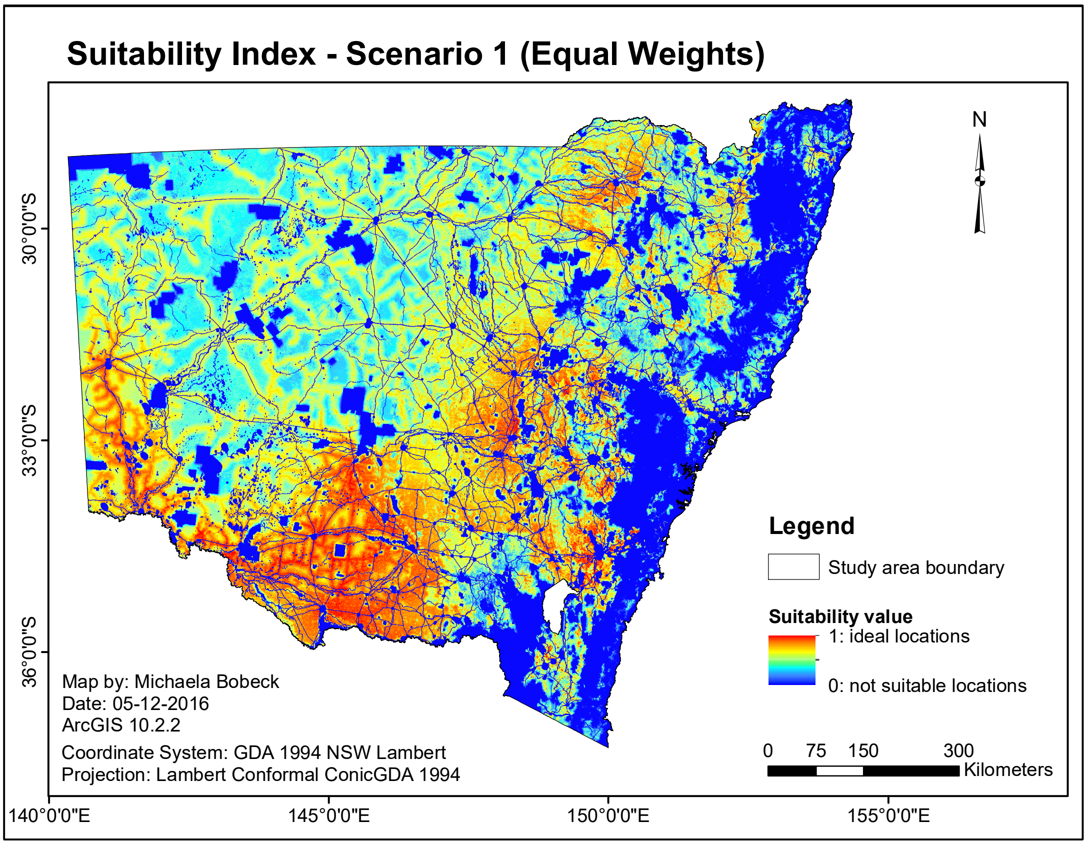

Figure 21. Suitability index based on Scenario 1 (equal weights).

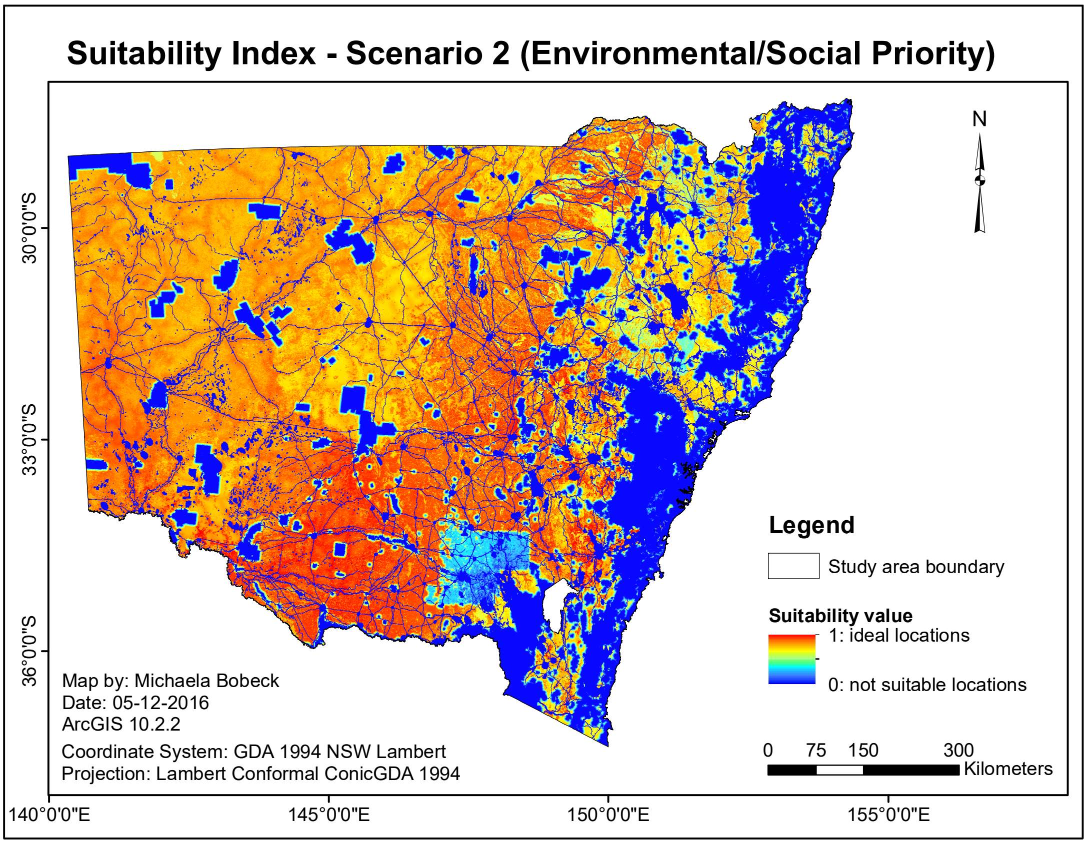

Figure 22. Suitability index based on Scenario 2 (environmental/social priority).

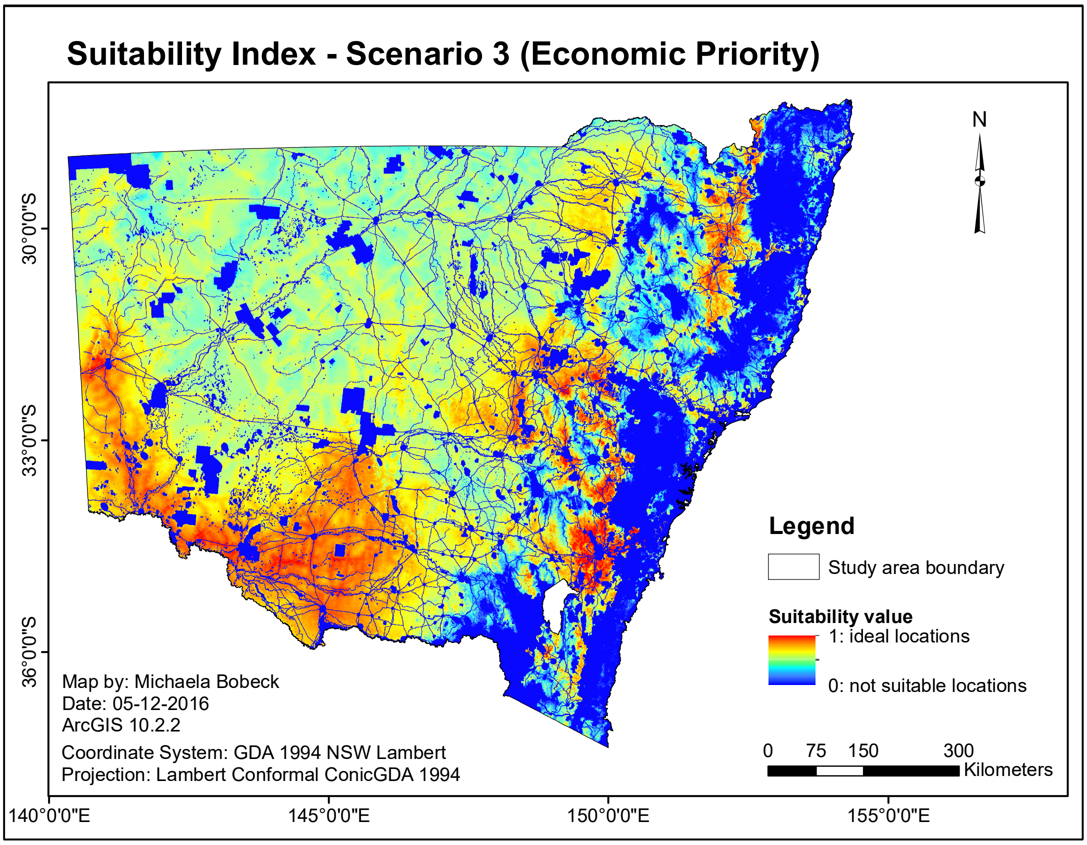

Figure 23. Suitability index based on Scenario 3 (economic priority).

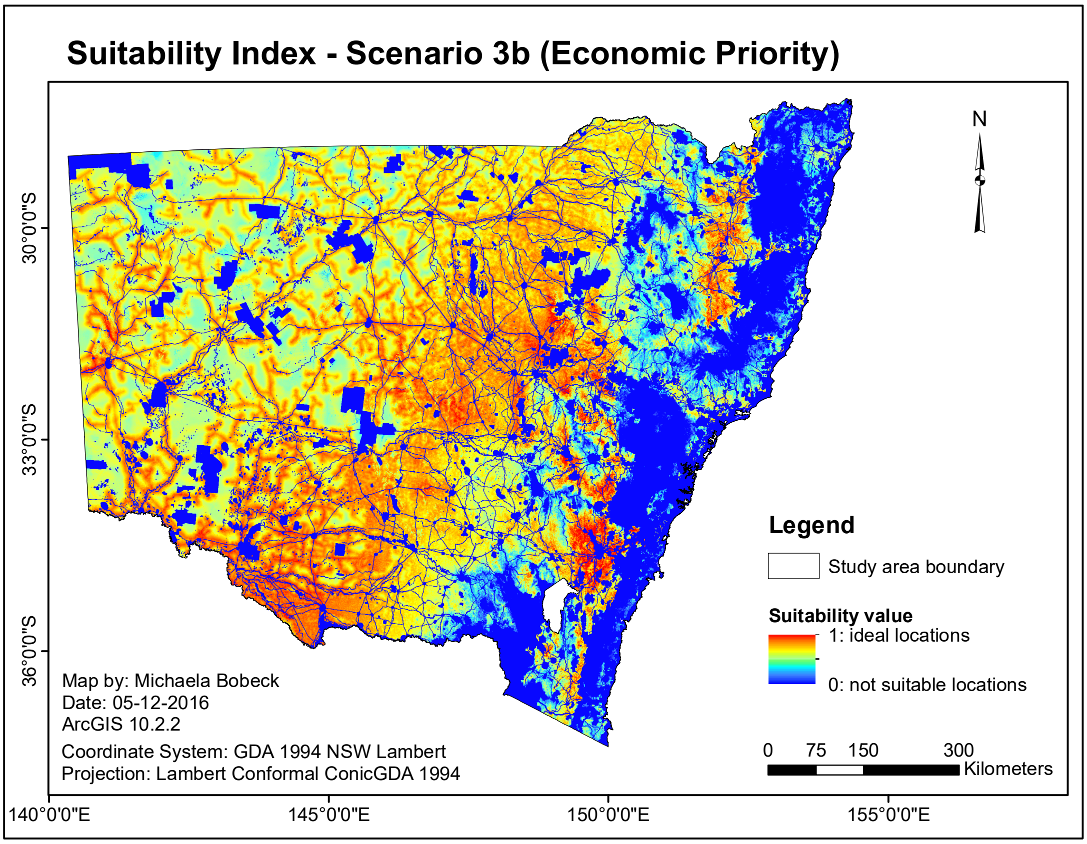

Figure 24. Suitability index based on Scenario 3b (economic priority).

5.4 Priority Areas

The reclassified suitability index maps with detailed priority areas are presented in Figure 25 to Figure 27. Priority areas are also listed in Table 12, which shows the percentage of land with 'high suitability' (SI > 0.75) in relation to total administrative area, as well as the total area of 'high suitability' in respective policy scenario. It is worth noting that in Scenario 1, 74 LGAs (including unincorporated NSW) have ≥50 percent of their respective land area deemed 'acceptable' for wind farm development (0.50 < SI ≤ 1). Similarly, 72 LGAs (including unincorporated NSW) were identified in Scenario 2 and 68 LGAs (including unincorporated NSW) in Scenario 3.

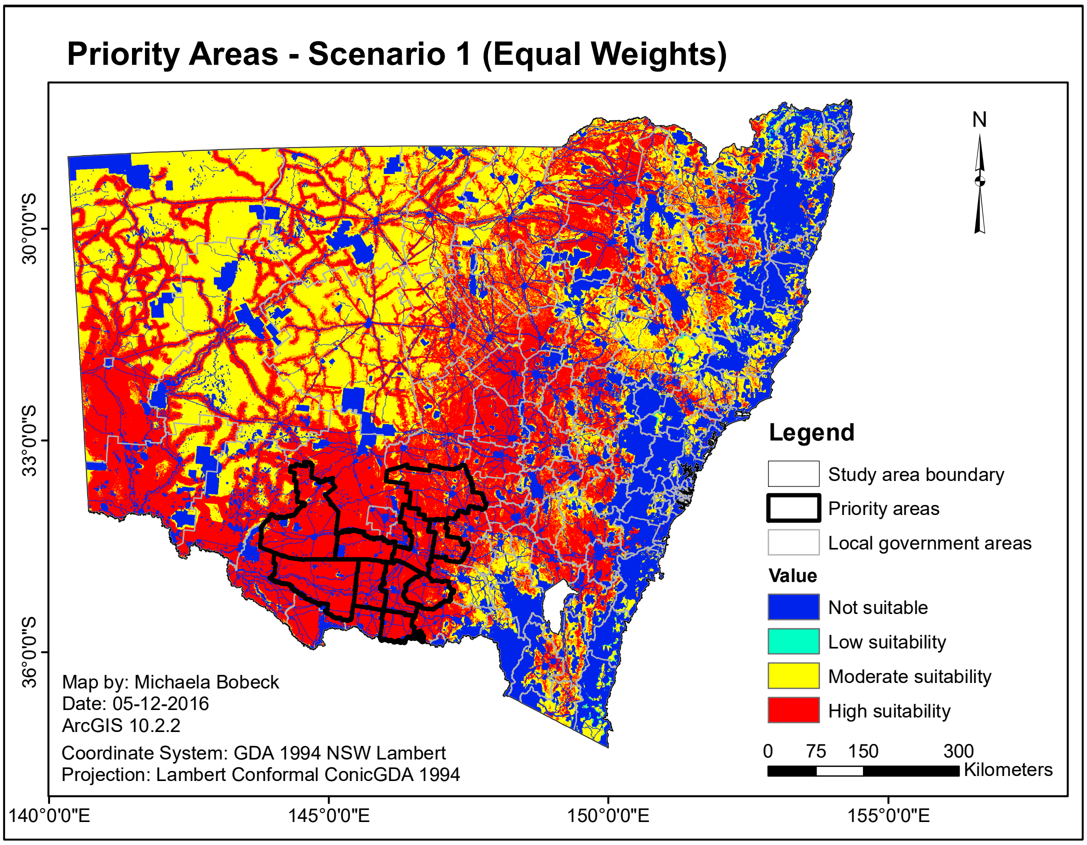

Figure 25. Priority areas in Scenario 1 (equal weights).

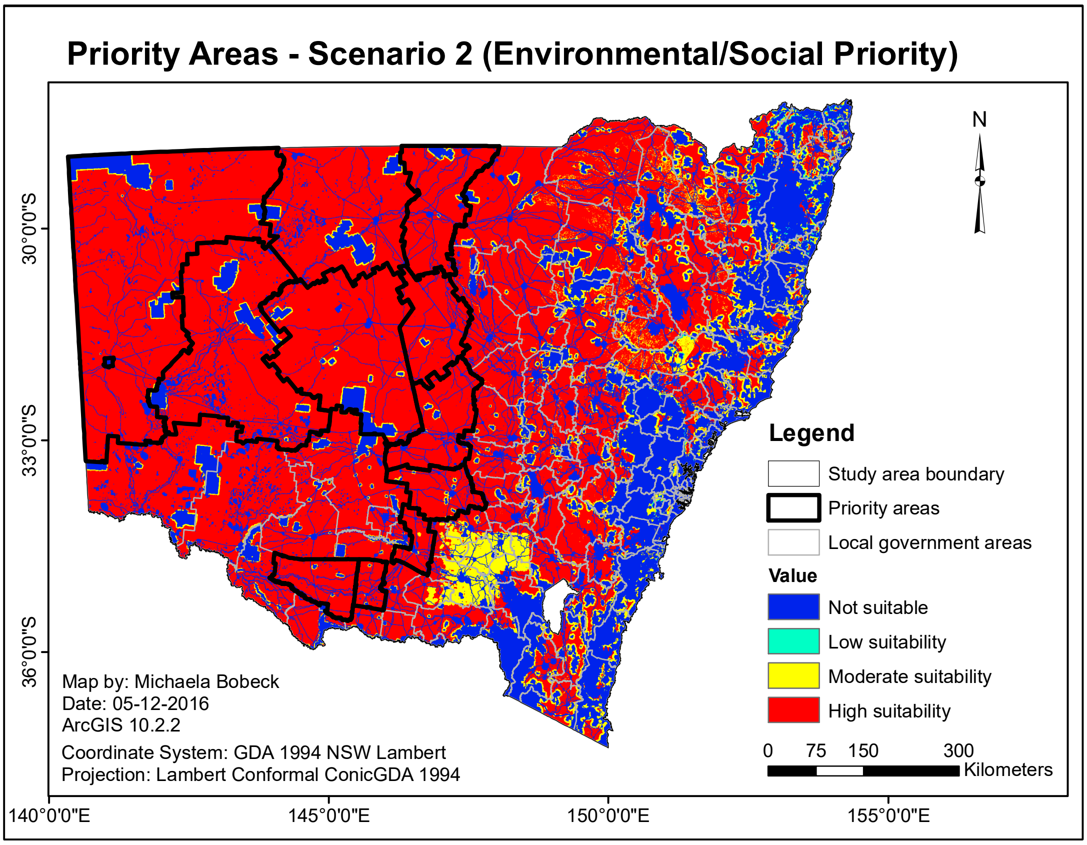

Figure 26. Priority areas in Scenario 2 (environmental/social priority).

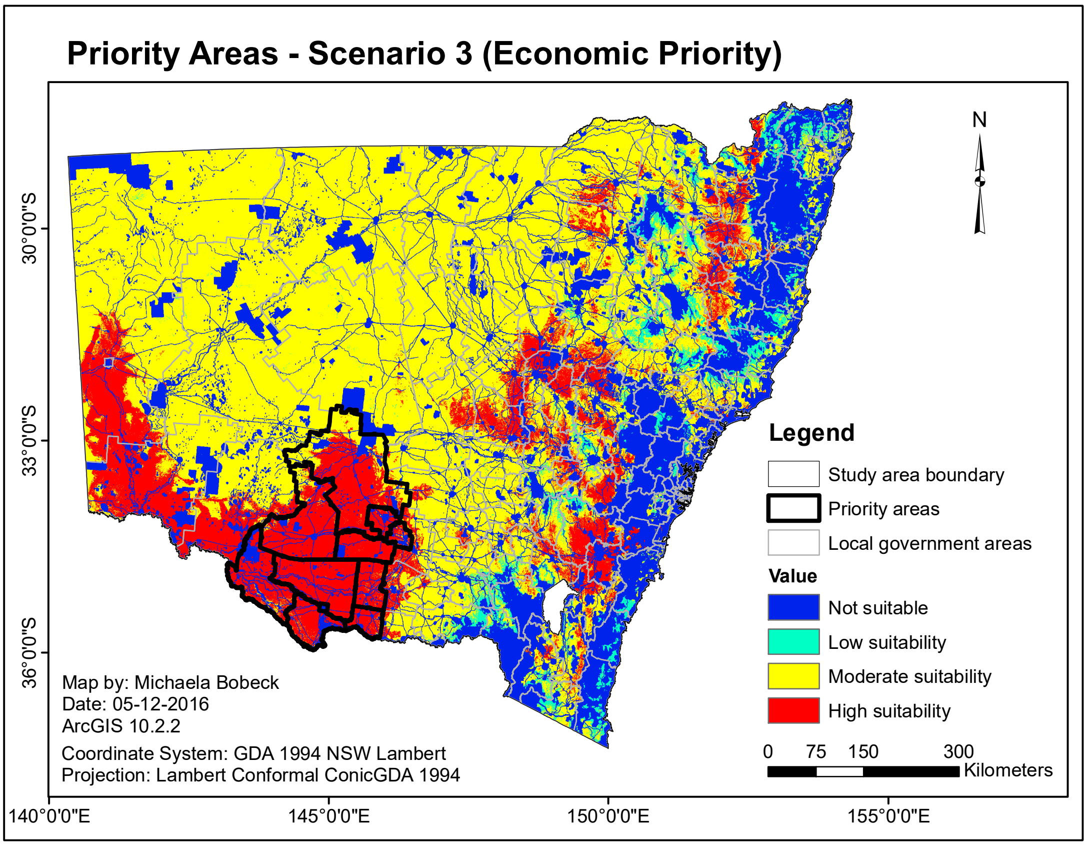

Figure 27. Priority areas in Scenario 3 (economic priority).

Table 12. Summary of priority areas for respective policy scenario.

Policy Scenario	LGA/Region Name	Percent of 'High Suitability' (%)	Total Area of 'High Suitability' (km^2)
1 – Equal Weights	Conargo	87	7605
	Jerilderie	86	2898
	Narrandera	83	3431
	Hay	82	9318
	Murrumbidgee	81	2833
	Lockhart	80	2302
	Urana	80	2669
	Bland	78	6675
	Corowa Shire	78	1808
	Coolamon	77	1863
2 – Environmental/Social Priority	Bogan	90	13063
	Lachlan	87	12926
	Unincorporated NSW	87	81188
	Cobar	86	39075
	Conargo	86	7545
	Jerilderie	85	2864
	Brewarrina	84	16195
	Narrandera	83	3435
	Bland	82	7121
	Central Darling	81	43653
3 – Economic Priority	Conargo	87	7631
	Jerilderie	84	2819
	Murrumbidgee	81	2850
	Hay	76	8543
	Berrigan	73	1515
	Griffith	73	1201
	Murray	66	2855
	Wakool	63	4763
	Leeton	57	666
	Carrathool	56	10543

5.5 Most Suitable Locations

The most suitable locations (point data) according to the developed decision support tool are detailed in Figure 28. The three policy scenarios present very similar results, with the most suitable locations identified within the following LGAs: Goulburne Mulwaree; Mid-Western Regional; Oberon; Upper Lachlan Shire; and Wingecarribee.

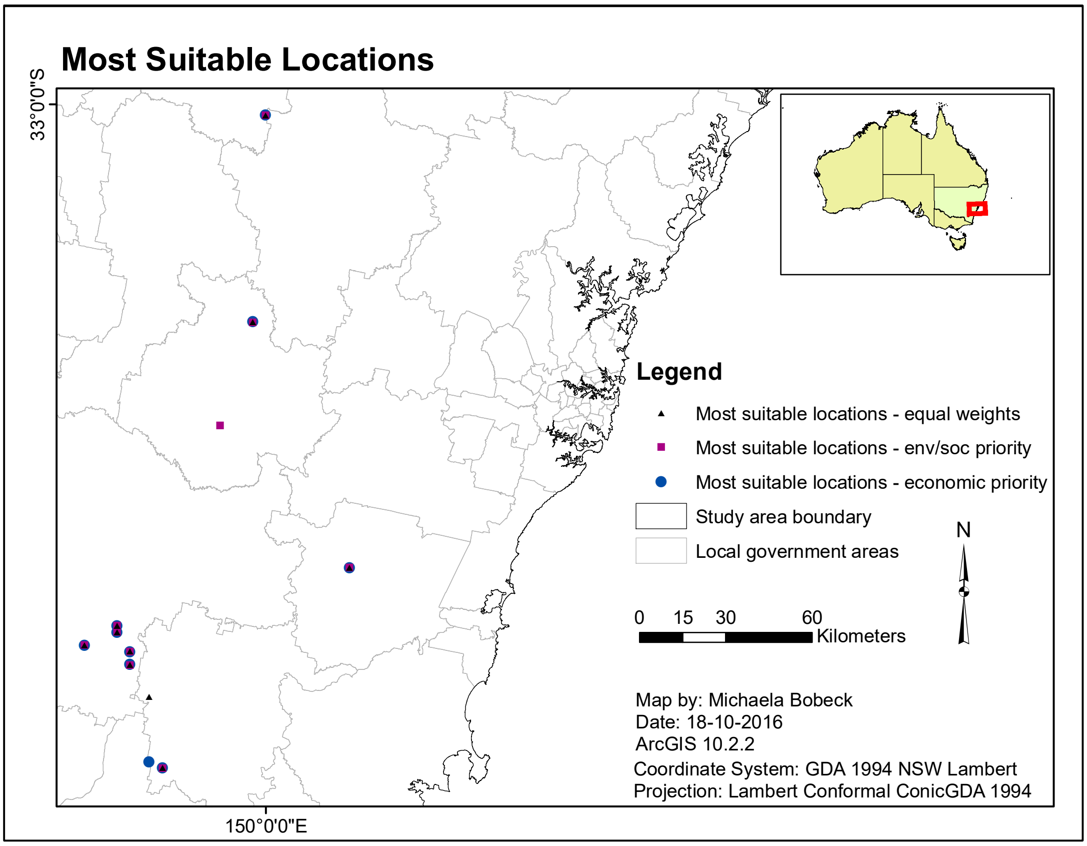

Figure 28. Most suitable locations according to the developed decision support tool.

5.6 Assessment of Existing Wind Farm Locations

The suitability index score of existing wind farm locations in each policy scenario are presented in Table 13. As can be interpreted from Table 13, over 80 percent of existing wind farm locations meet the decision constraint criteria defined in this study. However, Hampton Wind Park is situated within an exclusion zone with reference to decision constraint criteria C6 (safety restrictions); and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Energy Centre Wind Facility is situated within an exclusion zone with reference to decision constraint criteria C2 (built-up areas), C4 (environmental protection) and C6 (safety restrictions).

Furthermore, with respect to the wind farm locations which meet the defined decision constraint criteria; 100 percent of the existing wind farm locations were found to score above the 'high suitability' threshold (SI > 0.75) in Scenario 2, followed by 78 percent in Scenarios 1 and 3. Moreover, the mean SI score of the existing wind farm locations in each policy scenario ranges between 0.80 and 0.88 (excluding wind farm locations which do not meet the decision constraint criteria defined in this study). It is also interesting to note that all but one (Boco Rock Wind Farm) of these existing wind farm locations represent 'acceptable' locations, with a SI score greater than 0.50.

Moreover, the majority of existing wind farm locations is situated within close proximity to the most suitable locations identified in this study. The locations of existing wind farms in relation to the most suitable locations are depicted in Figure 29, where existing wind farms are labelled with their respective reference number as listed in Table 13.

Table 13. Suitability index scores of existing wind farm locations for scenarios.

Ref.	Wind Farm Name	Scenario 1 (Equal Weights)	Scenario 2 (Env./Soc. Priority)	Scenario 3 (Economic Priority)
		Suitability Index Score		
1	Blayney Wind Farm	0.83	0.96	0.73
2	Boco Rock Wind Farm	0.67	0.85	0.50
3	Capital I Wind Farm	0.82	0.90	0.81
4	Crookwell Wind Farm	0.84	0.86	0.93
5	CSIRO Energy Centre Wind Facility	0	0	0
6	Cullerin Range Wind Farm	0.82	0.90	0.81
7	Gullen Range Wind Farm	0.84	0.90	0.86
8	Gunning Wind Farm	0.81	0.88	0.87
9	Hampton Wind Park	0	0	0
10	Taralga Wind Farm	0.72	0.76	0.76
11	Woodlawn Wind Farm	0.88	0.91	0.91

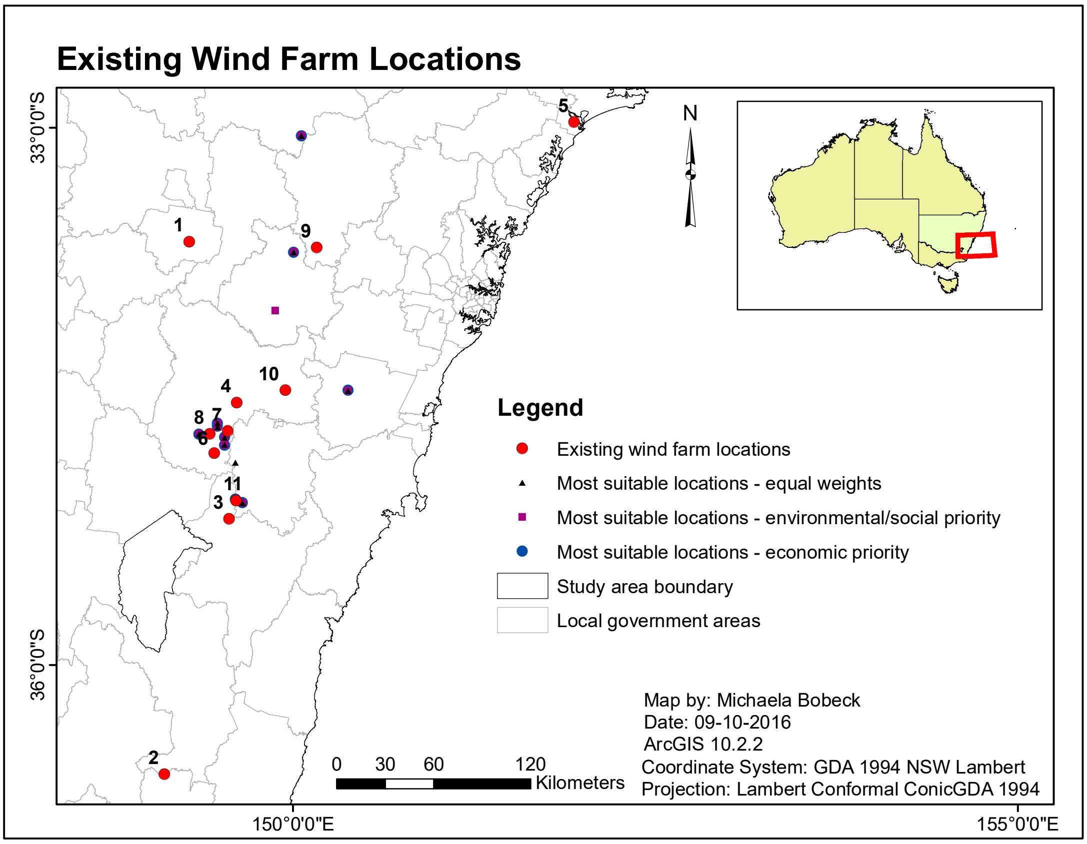

Figure 29. Existing wind farm locations and identified priority locations.

6. Discussion

6.1 Data Collection and Pre-Processing

The present study is based on publically available spatial data in vector or raster format. The input spatial resolution of the raster datasets vary between 30 m and 1 km, and the spatial scale at which vector data is represented also differs. Baban and Parry (2001) recognise in their study the composite suitability maps are generally less accurate than the least accurate layer used in its composition. Similarly, this is also true for the present study.

A high-resolution cell size of 150 x 150 m was here deemed suitable for the representation of decision criteria, as well as the GIS-based WLC procedure performed in this study. According to Malczewski (2000), high spatial resolution data, or disaggregated data, is generally preferred in GIS-based WLC since one of the assumptions underlying WLC is that each criterion in the set of decision criteria is independent of the other (no correlation between factors), which is less likely to be achieved if the input data is more aggregated. A cell size of 150 x 150 m was also applied in the study by Latinopoulos and Kechagia (2015). Moreover, it is worth noting that the spatial resolution of the input data and raster analysis was also restricted due to data availability and the processing extent (magnitude of the study area); and that a change in the input and/or analysis cell size could potentially generate different results.

Furthermore, the completeness of the input datasets varies, which in turn may affect the accuracy of the GIS-based WLC results. For example, input data for decision factor F4 (proximity to transmission network) does only include transmission network data according to Wade et al. (2016); and, as such, does not represent all opportunities for wind farms to connect to the electricity grid. Furthermore, according to the Office of Environment and Heritage (2015a) data on CEECs, included in decision factor F6 (distance from ecologically significant areas), does not include all listed CEECs. Similarly, according to the Office of Environment and Heritage (2010), data on critical habitat does not include the location of some critical habitat areas (Wollemi Pine e.g.) where disclosing the location would expose the habitat to a significant threat. It should also be noted that input data on wind speed, at a height of 100 m above ground level, is derived from modelling output only and has not been validated towards observations. Nevertheless, the completeness of the here applied data is deemed suffice for the purpose of this study, and also considered in line, if not beyond, the attributes included in related decision criteria in previous studies (Aydin et al., 2010; Latinopoulos & Kechagia, 2015; Watson & Hudson, 2015).

Moreover, the present study uses the NSW state boundary (off-shore areas excluded) as study boundaries and hence does not consider neighbouring states in regards to the defined decision criteria. Therefore, some areas in the periphery of the study area may potentially be inaccurately mapped with reference to potential opportunities or constraints in the neighbouring states.

6.2 Methodology

6.2.1 Decision Criteria Identification and Analysis

The number of attributes considered in the set of decision criteria defined in this study was in line with previous studies (Baban & Parry, 2001; Aydin et al., 2010; Latinopoulos & Kechagia, 2015; Watson & Hudson, 2015); and deemed appropriate with reference to Malczewski and Rinner (2015), who state that the number of criteria should be kept minimal, or as small as possible. Nevertheless, it is recognised that inclusion of several other attributes could prove valuable to the study including, but not limited to the following:

- Electricity demand/consumption;
- Grid integration/capacity/saturation;
- Soils and ground conditions;
- Proximity to ridges, hills i.e.;
- Mineral resources;
- Land value and price of acquisition; and
- Bushfire risk.

In respect to decision factors F4 (proximity to transmission network), F5 (proximity to road network), F6 (distance from environmentally significant areas) and F7 (distance from culturally significant features), it should also be noted that distance calculations are based on the Euclidean distance (straight-line distance) and as such do not consider topography i.e.

Additionally, this study investigates the overall land suitability covering both small and large scale wind farms, as well as a non-specific wind turbine height. As such, one may find that some areas are 'inaccurately' mapped, with respect to the defined decision criteria, considering the characteristics of an individual wind farm development. For example, input wind speed data is based on modelled wind speed at a height of 100 m; hence, smaller wind turbines would not access such high wind speeds as indicated in this study. Consequently, the site suitability attributes included in the present study should always be considered in a more detailed site assessment and with respect to the nature of the proposed wind farm. Coppin et al. (2003) also outlines that monitoring of the wind, at or near hub height, to confirm the predicted wind resource at the site is one of the major steps of wind farm site selection. Furthermore, previous studies do not report on a specific wind turbine size or capacity for their site suitability assessments neither (Baban & Parry, 2001; Aydin et al., 2010; Latinopoulos & Kechagia, 2015; Watson & Hudson, 2015).

6.2.2 MCDA and Compilation of Suitability Index

Malczewski and Rinner (2015) recognise how integrating MCDA into a GIS environment provides a methodology for introducing a decision maker's value judgements into GIS-based decision making. Nevertheless, the main purpose of GIS-based MCDA should not be to identify the 'best' solution, but to assist decision makers in the understanding of complex spatial decision problems and the development of a suitable evaluation approach. Moreover, the MCDA performed in this study is based on the WLC and AHP methods, which are both common techniques for spatial suitability assessments (Malczewski & Rinner, 2015).

Additionally, the AHP was chosen as a suitable method to derive weights for decision factors due to the simplicity of the method, as well as the possibility for integration with GIS. The Department for Communities and Local Government (2009) also recognises that the strengths of the AHP method include the benefit of helping decision makers to structure and understand the decision problem, as well as enabling some cross-checking to be accomplished. The AHP is also considered a suitable method where the input information is based on judgements rather than measurements of performance.

Furthermore, AHP has been successfully applied in Bennui (2007) and Al-Yahyai et al., (2012); WLC applied in Hansen (2005); and the combination of WLC and AHP applied in Latinopoulos and Kechagia (2015). Nevertheless, this study recognises that there are some disadvantages with the applied methods, which are discussed below.

According to Malczewski (2000) the major disadvantage of the commonly used GIS-based WLC methods is that these often use ad-hoc approaches with limited theoretical foundation. Furthermore, underlying assumptions of the WLC method are often ignored. For example, the establishment of decision criteria is often a data availability driven process, which typically results in an incomplete set of decision criteria. However, Malczewski (2000) also recognise that is generally very difficult to achieve some of the underlying assumptions in spatial decision problems, for example that the set of decision criteria is decomposable and non-redundant.

Moreover, the AHP method has been subject to criticism amongst decision analysts, including Malczewski (2000) who raises concerns about the 1-9 value scale and corresponding description not having a firm theoretical foundation, or reference to units or scales, on which the factors are measured. Hence, decision makers may interpret the pairwise comparisons inconsistently and in potentially 'inaccurate' ways.

Furthermore, value function analysis for deriving standardised decision factors is considered best practice and an approach which could greatly improve the 'accuracy' of the WLC results (Malczewski, 2000). Hence, the application of the fuzzy sets theory for standardisation of decision factors introduced in this study is deemed an appropriate methodological choice.

Nevertheless, it is noteworthy that the type of fuzzy membership function applied indirectly influences the relative 'weight' of respective decision factor. In this study, decision factors were standardised using a linear membership function; nonetheless, other function types exist, which potentially could have been more suitable for representation of for example wind speed in relation to available wind energy i.e. However, due to the spatial resolution of the available wind speed input data, and the fact that the actual wind speed in the real-world may vary within each grid cell of modelled wind speed data; an exponential membership function (J-shaped) could for example generate substantially 'false' membership results. Hence, a linear function was interpreted to be an appropriate choice for the purpose of this study. In addition, linear membership functions have been used to represent decision factors in several other studies, including Hansen (2005), Aydin et al. (2010) and Latinopoulos and Kechagia (2015), where the latter also represented wind speed with a linear membership function.

Moreover, the policy scenarios established in this study are solely based on the author's knowledge and subjective judgements. Pairwise comparisons between decision factors, and subsequently suitability index results, may therefore differ from judgements and analysis results generated by decision makers in a real-world planning context. Furthermore, by incorporating additional decision factors into the MCDA, the weights would also be modified.

Additionally, whilst the WLC and AHP (pairwise comparisons) methods were deemed suitable for the present study; other decision rules (proximity-adjusted WLC, ordered weighted averaging and outranking methods i.e.) and weight estimation techniques (ranking and rating methods i.e.) exist, which may yield different results.

6.2.3 Identification of Priority Areas and Most Suitable Locations

Another discussion point is the methodology used for the identification of priority areas. In this study, the administrative boundaries of LGAs were applied as 'boundaries' for priority areas; and the ten LGAs with the greatest percentage of high suitability land, relative to their respective administrative area, were nominated as priority areas. As such, the analysis results are believed to indicate LGAs where the possibility of identifying highly suitable wind farm locations in the real-world context is higher, compared to remaining LGAs. This approach was deemed appropriate given the capabilities of 'ArcGIS 10.2.2 for Desktop Advanced'', as well as available input data. Nevertheless, since the priority areas do not cross-over the LGA boundaries, the analysis results do not indicate the most suitable 'regions' across NSW. Moreover, if only the total area of high suitability land within each LGA was to be considered (not with respect to the individual LGA area), different analysis results would be generated, with priority areas generally identified further west than in the applied methodology. This alternative analysis approach was however deemed less appropriate considering the population density and the location of major energy consumption areas (urban/industrial areas i.e.) in NSW;

where according to the Australian Bureau of Statistics (2016), the highest population density is found along the east coast and hence also the major energy consumption areas.

In context of the above, another possibly suitable analysis approach for the identification of priority areas is the 'Locate Regions' tool in the 'ArcGIS Pro' software. This method uses a parameterized region-growing algorithm to identify regions based on an evaluation criterion such as the 'highest sum', which also meet the defined size and spatial constraints. Also Brookes (1997) suggests using parameterised region-growing programming to identify the 'best' regions in a suitability map, and to deal with the issue of highest ranked cells not being clustered when ranking grid cells based on raster GIS. The 'ArcGIS Pro' software was however not available for use in this project.

Furthermore, in order to calculate statistics and subsequently allow identification of priority areas, it was in this study deemed necessary to reclassify the suitability index. Reclassification of the suitability index was also performed by Al-Yahyai et al. (2012), and Watson and Hudson (2015), who both applied four classes of varying intervals. Latinopoulos and Kechagia (2015) also discuss the suitability index results of their study by introducing suitability thresholds similar to the ones in the present study, where a SI value of ≥ 0.5 was interpreted to be acceptable and SI ≥ 0.7 a high score. Similarly, Watson and Hudson (2015) applied a threshold of 0.7 for their reclassification of 'most suitable' areas. Moreover, it should be mentioned that by changing the thresholds of the suitability classes used in this study (see Table 8), different results and priority areas could potentially be generated.

In order to identify the most suitable locations (point data), it was considered necessary to resample the final suitability index to incorporate the minimum land size required for a potential wind farm development. This approach is also supported by Eastman et al. (1993) who argue that the best approach in GIS-based WLC is to process input data at a higher spatial resolution, followed by aggregation of grid cells to identify the best alternative (location) of a larger extent. However, this study did not apply the 'Aggregate' tool in ArcGIS Spatial Analyst toolbox, but instead used the 'Resample' tool in the ArcGIS Data Management toolbox, with the bilinear interpolation resampling technique. This approach was deemed appropriate since it determines the new cell value based on a weighted distance average of the four nearest input cell centres, contrary to the 'Aggregate' tool which uses for example the mean or maximum cell values of all input cells to compute the new cell value. Furthermore, the cell size for the resampled SI was based on the minimum size of land required for wind farm development according to Nelson (2013); however, the cell size could easily be modified to identify ideal locations based on a larger (or smaller) wind farm land size.

6.3 Results

6.3.1 Decision Constraints Analysis

The extent of the composite constraint layer in this study accounts for approximately 27.6 percent of the entire study area, and thus indicates potential development sites (feasible areas) across the majority of NSW. As depicted in Section 5.1, the spatial extent of the individual decision constraints vary, with decision constraint C4 (environmental protection) demonstrating the greatest area of exclusion zones, corresponding to approximately 19.3 percent of the entire study area. Also decision constraint C3 (land use restrictions) details a great extent of exclusion zones, covering approximately 10.9 percent of the study area.

Moreover, it should be noted that wind farms may be 'permitted with consent' in additional land use zones in a council's local environmental plan. Due to the spatial extent of land use restrictions within the eastern parts of NSW, where the majority of major energy consumption areas (urban/industrial areas i.e.) are situated, one could also argue that councils should be urged to consider this option for areas where wind suitability would otherwise be high and the specific land use at the site could prove acceptable for wind farm development. Furthermore, in regards to the extent of exclusion zones relating to decision constraint C4 (environmental protection), and with particular reference to the eastern parts of NSW, it might similarly be argued that the defined decision constraint criteria is excessively comprehensive. However, from a sustainable development perspective it is recognised that Australia has unique and diverse ecosystems and landscapes, which should be protected from any potential negative effects of wind farm developments. Nevertheless, whether some areas deemed to represent environmental protection zones in this study could prove suitable for wind farm development in a real-world context is beyond the scope of the present study.

It is also interesting to note that the result of the composite constraint analysis are much favourable compared to similar studies. Tegou et al. (2010) reported a composite constraint map comprising 56.8 percent of their study area in Lesvos island, Greece; Latinopoulos and Kechagia (2015) had a constraint layer accounting for 83 percent of the study area in the region of Kozani, Greece; and in Watson and Hudson (2015) the environmental constraint layer only comprised 62.2 percent of their study area in southern England.

In context of the above, the extent of potential development sites (feasible areas), identified in the present study, could potentially or partly be a reflection of the spatial resolution of input data and the common cell size applied in the WLC analysis. Furthermore, the abovementioned similar studies all included the slope attribute in their set of decision constraints; however, with varying thresholds ranging between 10 and 30 percent. Nevertheless, approximately 93 percent of the study area in this study, based on an analysis cell size of 150 m, have a slope gradient below 25 percent. Therefore, it is not believed that inclusion of 'slope gradient' in the set of decision constraints established in this study would greatly decrease the extent of feasible areas. Instead, the extent of feasible areas identified in this study is thought to rather be explained, at least in part, by the magnitude of the study area; where for example NSW is thought to have a less dense spatial distribution of built-up areas, roads and cultural protection areas i.e. compared to similar studies.

6.3.2 Standardisation of Decision Factors

The standardisation of the here established decision factors indicate a varying degree of wind farm site suitability across NSW. The mean membership value of each decision factor raster layer is deemed to reflect the general suitability of each respective decision factor. Consequently, it appears that the majority of decision factors generally present a high suitability across NSW, with a mean membership value above the 'high suitability' threshold of SI > 0 .75. However, decision factors F4 (proximity to transmission network) and F3 (land cover), as well as F1 (wind speed), present a 'lower' mean membership value and could thus be considered the dominant factors in restricting site suitability in this study. Similarly, Latinopoulos and Kechagia (2015) identified wind speed as the dominant restricting factor of land suitability in their study. Furthermore, the influence of land cover was there apparent; however, not as important as in the present study.

6.3.3 MCDA and Suitability Index for Respective Scenario

The reclassification of the final suitability index for each scenario indicates that, according to the developed decision support tool, the majority of the entire study area (approximately 70 percent) is considered 'acceptable' (0.50 < SI ≤ 1) for potential wind farm development in all three investigated policy scenarios. Consequently, the results of this study support wind energy as a viable option to help expand the renewable energy market in NSW. It is also worth noting that the degree of 'acceptable' wind farm locations, identified in the present study, is much greater compared to for example Latinopoulos and Kechagia (2015) who found only 12 percent of their study area in Greece to present 'acceptable' SI scores (SI > 0.50). This relatively low degree of acceptable locations identified by Latinopoulos and Kechagia (2015) is thought to be a reflection of the wind speed characteristics of their study area, where the majority of the study area is interpreted to represent a 'low' site suitability and with only 0.1 percent satisfying the upper threshold value (p-value) of 7.5 m/s.

Furthermore, this study generally indicates a relatively large extent of 'high suitability' (SI > 0.75) across the study area. According to Table 11, Scenario 2 (environmental/social priority) demonstrates the largest total area of 'high suitability', corresponding to 65.3 percent of the entire study area, followed by 40.0 percent of the study area in Scenario 1 (equal weights) and 15.1 percent of the study area in Scenario 3 (economic priority). Compared to similar studies, these figures are also considered substantial. For example, in the study by Gorsevski et al. (2013), the high suitability scores (SI > 0.8) accounted for

only 1.5 percent of their study area in the scenario incorporating economic factors, and 29.4 percent of their study area in the scenario incorporating environmental factors; in Latinopoulos and Kechagia (2015), areas of high SI scores ($SI \geq 0.7$) comprised 2.2 percent of their study area in the economic/technical oriented policy scenario, and 11.8 percent of their study area in the environmental/social oriented policy scenario; and in Watson and Hudson (2015), the 'most suitable' category ($SI > 0.7$) accounted for less than 0.1 percent of their non-constraint area in all investigated scenarios.
The degree of 'high suitability' land and 'acceptable' wind farm locations identified in this study may potentially, at least partly, be a reflection of the here identified decision factors and associated weights, the spatial resolution of the input data and the common cell size applied in the WLC analysis, as well as the magnitude of the study area. Additionally, it is noted that NSW generally has very good wind resources and a less dense spatial distribution of constraint areas such as built-up areas, roads and cultural protection areas i.e. compared to similar studies.

Moreover, the differences between the investigated policy scenarios in regards to the distribution and extent of 'high suitability' land, indicate that the economic criteria are generally more difficult to meet. This result is also similar to the findings of Latinopoulos and Kechagia (2015) and Gorsevski et al. (2013). Furthermore, the variation in site suitability presented in Section 5.3 suggest that the developed decision support tool is somewhat sensitive to changes in policy objectives. Nevertheless, as depicted in Scenario 3b (economic priority), the suitability in Scenario 3 could easily be improved by incorporating the larger electricity network (sub-transmission and high voltage distribution) into the MCDA. Additionally, according to Dunstan et al. (2011), the capital expenditure on the electricity network infrastructure in NSW is significant and not predicted to decline; however could be reduced through decentralised energy strategies. As such, it could potentially also be argued that the extent of 'high suitability' in Scenario 3 could be increased by incorporating the economic viability of decentralised energy systems and avoidance of long-distance transmission lines. Similarly, the present study may also be used as a tool to identify suitable areas for decentralised energy systems incorporating wind energy.

6.3.4 Priority Areas and Most Suitable Locations

Priority areas were here defined as areas of particular interest for further investigation, due to the high concentration of highly suitable land, which may represent an increased probability to identify ideal wind farm locations in the real-world context. As can be interpreted from Table 12, and Figure 25 to Figure 27, the three policy scenarios investigated in this study indicate varying geographical positions of identified priority areas, which similarly to the final SI results of 'high suitability' land indicate that the developed decision support tool is relatively sensitive to changes in policy objectives. Nevertheless, priority areas were consistently located within the southern parts of central NSW, in particular in Scenario 1 (equal weights) and Scenario 3 (economic priority), which present more similar locations of priority areas compared to Scenario 2 (environmental/social priority). It should also be noted that two LGAs, Conargo and Jerilderie, were identified as priority areas in all three policy scenarios.

Furthermore, according to Malczewski and Rinner (2015), the assignment of weights is one of the key sources of uncertainty in MCDA. As such, in order to identify priority areas one could hence argue that areas which are susceptible to slight changes in suitability, depending on the allocation of weights, should be eliminated, and only areas considered to be of high suitability in all investigated policy scenarios should be selected for a more detailed suitability analysis. In this context, it is deemed to be of interest to conduct a more detailed evaluation of site suitability primarily within the LGA areas of Conargo and Jerilderie.

In regards to the analysis of priority areas, it is also thought interesting to here introduce the concept of the Regional Clean Energy Program implemented in NSW. This program was implemented to provide communities with information and resources to promote renewable energy options, and introduced the concept of renewable energy precincts. The selection of renewable energy precinct areas was initially only based on areas with the best known wind resources (Department of Environment, Climate Change & Water, 2010), but was later updated to cover a broader area across NSW (Office of Environment and Heritage, 2016). It is further noteworthy that in the present study, the identified priority areas are all located outside the initially defined renewable energy precincts; however, within the currently defined boundaries of the South West and North West renewable energy precincts. These results further suggest that wind speed may not be the only important aspect for identifying suitable wind farm locations and that areas located outside the initially defined precincts (areas with the best known wind resources) also should be investigated for wind farm suitability.

Moreover, the most suitable locations (point data) identified in each investigated policy scenario, indicate almost identical geographical positions; however, divergent from the location of identified priority areas. These results, contrary to the final SI results of 'high suitability' land and priority areas, suggest that the relative importance of decision factors is close to negligible. It is further interesting to note that the decision support tool developed by Latinopoulos and Kechagia (2015) indicated a much higher sensitivity in the context of identifying the most suitable locations.

6.3.5 Existing Wind Farm Locations

The analysis of existing wind farm locations presents high suitability scores for the majority of the wind farms, with nine wind farms out of eleven located within areas mapped as 'feasible' by the developed decision support tool. However, it is noted that the capacity of the two wind farms (CSIRO Energy Centre Wind Facility and Hampton Wind Park) located within the established 'exclusion zones' is 0.16 MW and 1.2 MW, and hence considerably lower than the 5 MW threshold used by Wiser et al. (2011) to describe the typical minimum capacity of wind farms. Likewise, existing wind farms located within areas deemed 'feasible' in this study all have an individual capacity above 5 MW. Therefore, it could be argued that the decision criteria established in this study are not applicable for the CSIRO Energy Centre Wind Facility and Hampton Wind Park due to their relatively low capacities.

It is further worth noting that the majority of existing wind farm locations presents SI scores above the 'high suitability' threshold (SI > 0 .75) in all three scenarios, and that the mean SI score of the existing wind farm locations in each policy scenario ranges between 0.80 and 0.88 (excluding wind farm locations which do not meet the decision constraint criteria defined in this study). Additionally, all but one (Boco Rock Wind Farm) of these existing wind farm locations represent 'acceptable' locations, with a SI score greater than 0.50.

Moreover, the generally high SI scores of the existing wind farm locations, suggest that the developed decision support tool may prove valuable when analysing suitable wind farm locations within a planning or decision making context in NSW. This is further supported by the fact that the existing wind farm locations are all within relatively close proximity to the most suitable locations identified in the present study.

Furthermore, with respect to the wind farm locations which meet the defined decision constraint criteria, it is also interesting to note that 100 percent of existing wind farms were identified within 'high suitability' areas in Scenario 2 (environmental/social priority), compared to 78 percent in Scenarios 1 (equal weights) and 3 (economic priority). This could potentially indicate that environmental priorities are often upheld within the current planning and decision making processes concerning wind farm development in NSW.

7. Conclusions

This study presents a GIS-based MCDA approach to evaluate wind farm site suitability across NSW from a sustainable development perspective, based on user inputs and publically available spatial data. As such, a decision support tool was developed that is capable of handling multiple decision criteria covering economic, environmental and social aspects of wind farm planning.

In conclusion, the results of this study indicate great development potential for wind energy in NSW, with approximately 70 percent of the study area deemed 'acceptable' for wind farm development. Furthermore, with respect to the identified research questions (see Section 1.1) the following overall conclusions can be made:

1. The developed decision support tool allows for identification of priority areas, as well as most suitable locations. The LGAs of Conargo and Jerilderie are recognised as priority areas in all three investigated policy scenarios and are hence deemed to be of particular interest for further evaluation. The most suitable locations are found within the LGAs of Goulburne Mulwaree, Mid-Western Regional, Oberon, Upper Lachlan Shire and Wingecarribee.
2. The analysis of 'high suitability' land and identified priority areas suggests that the developed decision support tool is somewhat sensitive to changes in policy objectives. Nevertheless, it should be noted that the three evaluated policy scenarios reported almost identical geographical positions of 'most suitable locations'.
3. The majority of existing wind farms are found within 'high suitability' areas, and eight out of eleven existing wind farm locations are situated in areas deemed to be 'acceptable'. However, two wind farms (CSIRO Energy Centre Wind Facility and Hampton Wind Park) do not meet the decision constraint criteria defined in this study.

Moreover, the methodology and scope of this project could be extended to incorporate expert or stakeholder input on decision criteria, as well as on pairwise comparisons of decision factors in the AHP. Furthermore, the present study was conducted at a state level; however, the developed decision support tool could also be applied at the national or local level, depending on available spatial data and planning objectives.

Finally, the results of this study suggest that the developed decision support tool could potentially assist wind farm developers and governments within a planning or decision making context in NSW. Nevertheless, this study is broad in nature and should therefore be considered with some caution, and by no means replace the need for a more detailed evaluation on site suitability for prospective projects.

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8. References

Al-Yahyai, S., Charabi, Y., Gastli, A. & Al-Badi, A., 2012. 'Wind farm land suitability indexing using multi-criteria analysis', *Renewable Energy*, vol. 44, pp. 80-87.

Australian Bureau of Statistics, 2011. *1259.0.30.001 - Australian Standard Geographical Classification (ASGC) Digital Boundaries, Australia, July 2011*. ESRI Shapefile format. Australian Bureau of Statistics, Canberra, Australian Government, http://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/1259.0.30.001July%202011?OpenDocument [09/03/2016].

Australian Bureau of Statistics, 2016. *3101.0 - Australian Demographic Statistics, Jun 2015*. Australian Bureau of Statistics, Canberra, Australian Government, http://www.abs.gov.au/ausstats/abs@.nsf/mf/3101.0 [04/03/2016].

Australian Greenhouse Office & Australian Wind Energy Association, 2004. *Wind Farm Siting Issues in Australia.* Prepared by Sustainable Energy Australia for the Australian Wind Energy Association and the Australian Government's Greenhouse Office, http://www.sustainableenergyaustralia.com.au/FAQs.html [24/03/2016].

Aydin, N. Y., Kentel, E. & Duzgun, S., 2010. 'GIS-based environmental assessment of wind energy systems for spatial planning: A case study from Western Turkey', *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 364-373.

Baban, S. MJ. & Parry, T., 2001. 'Developing and applying a GIS-assisted approach to locating wind farms in the UK', *Renewable Energy*, vol. 24, pp. 59–71.

Bennui, A., Rattanamanee P., Puetpaiboon, U., Phukpattaranont P., Chetpattananondh, K., 2007. 'Site selection for large wind turbine using GIS'. *PSU-UNS international conference on engineering and environment-ICEE-2007*, Phuket, Thailand, http://www.uni.edu/apetrov/wind/Weighted/Bennui2007.pdf [23/03/2016].

Bile, M., 2010. In support of wind energy: the foundations that underlie wind projects. AltEnergy, http://www.altenergymag.com/article/2010/04/in-support-of-wind-energythe-foundations-that-underlie-wind-projects/638/ [03/04/2016].

Brookes, J., 1997. 'A parameterized region-growing programme for site allocation on raster suitability maps.' *International Journal of Geographical Information Science*, vol. 11, pp. 375-396.

Chislett, D., 2016, email, 19 September, dustin.chislett@essentialenergy.com.au

Clean Energy Council, 2013. Best Practice Guidelines for Implementation of Wind Energy Projects in Australia. Clean Energy Council, Melbourne, Australia, https://www.cleanenergycouncil.org.au/technologies/wind-energy/best-practice-guidelines.html [22/03/2016].

Coppin, P.A., Ayotte, K.A. & Steggel, N., 2003. *Wind Resource Assessment in Australia – A Planners Guide*. Wind Energy Research Unit CSIRO Land and Water, http://www.ecocitizenaustralia.com.au/wp-content/uploads/2011/03/pis7.pdf [22/03/2016].

Dai, K., Bergot, A., Liang, C., Xiang, W. & Huang, Z., 2015. 'Environmental issues associated with wind energy – A review', *Renewable Energy*, vol. 75, pp. 911-921.

Department of Agriculture & Water Resources, 2016. *Land Use: New South Wales 2009 (ESRI Personal Geodatabase)*. Department of Agriculture & Water Resources, Canberra, Australian Government, http://www.agriculture.gov.au/abares/aclump/land_use/data-download [16/02/2016].

Department for Communities & Local Government, 2009. *Multi-criteria analysis: a manual*. Communities and Local Government Publications: Wetherby, West Yorkshire, United Kingdom, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7612/1132618.pdf [27/03/2015].

Department of Environment, Climate Change & Water, 2010. *Community Attitudes to Wind Farms in NSW*. Department of Environment, Climate Change & Water, Sydney, NSW Government, http://www.environment.nsw.gov.au/resources/communities/100947-wind-farms-community-attitudes.pdf [15/03/2016].

Department of Industry & Science, 2015a. *2015 Australian energy update*. Department of Industry, Innovation & Science, Canberra, Australian Government, http://www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Documents/aes/2015-australian-energy-statistics.pdf [03/03/2016].

Department of Industry & Science, 2015b. *Australian energy statistics.* Table O, August, Department of Industry, Innovation & Science, Canberra, Australian Government, http://www.industry.gov.au/Office-of-the-Chief-Economist/Publications/Pages/Australian-energy-statistics.aspx [04/10/2016].

Department of Planning & Environment, n.d. *Open Data*. Department of Planning & Environment, NSW Government, https://www.planningportal.nsw.gov.au/planning-tools/open-data [16/03/2016].

Department of Planning & Infrastructure, 2011. *Draft NSW Planning Guidelines Wind Farms*. Department of Planning & Infrastructure, NSW Government, http://www.planning.nsw.gov.au/Policy-and-Legislation/~/media/1C3284EB49E244FEA7539B8FFFD3D9BA.ashx [16/02/2016].

Department of Resources & Energy, 2014. *NSW Renewable Energy Action Plan.* Trade & Investment, NSW Government, http://www.resourcesandenergy.nsw.gov.au/energy-consumers/sustainable-energy/renewable-energy-action-plan [27/03/2015].

Dunstan, C., Boronyak, L., Langham, E., Ison, N., Usher, J., Cooper, C. & White, S., 2011. *Think Small: The Australian Decentralised Energy Roadmap: Issue 1, December 2011.* CSIRO Intelligent Grid Research Program. Institute for Sustainable Futures, University of Technology, Sydney, http://www.energetics.com.au/getmedia/64c9d825-2ff1-4baf-8656-c64aaaeada5c/Australian-Decentralised-Energy-Roadmap_December-2011_0-(1).pdf.aspx [16/09/2016].

Eastman, J. R., Kyem P. A.K. & Toledano, J., 1993. 'A Procedure for Multi - Objective Decision Making in GIS under Conditions of Conflicting Objectives'. *Proceedings of the Fourth European Conference and Exhibition on Geographical Information Systems, EGIS '93*. Genoa: EGIS Foundation, vol. 1, pp. 438-447.

Geoscience Australia, 2006. *GEODATA TOPO 250K Series 3.* Geoscience Australia, Canberra, Australian Government, http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_63999 [20/08/2016].

Geoscience Australia, 2010. *1 second SRTM Derived Smoothed Digital Elevation Model (DEM-S) version 1.0*. Geoscience Australia, Canberra, Australian Government, http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_aac46307-fce8-449d-e044-00144fdd4fa6/SRTM-derived+1+Second+Digital+Elevation+Models+Version+1.0 [16/03/2016].

Geoscience Australia, 2016. *National Location Information*. Geoscience Australia, Canberra, Australian Government, http://www.ga.gov.au/scientific-topics/national-location-information [16/02/2016].

Geoscience Australia & ABARE, 2010. *Australian Energy Resource Assessment*. Geoscience Australia, Canberra, Australian Government, http://arena.gov.au/files/2013/08/Australian-Energy-Resource-Assessment.pdf [20/09/2016].

Global Wind Energy Council, 2015*. Global Wind Report – Annual Market Update 2015*, Global Wind Energy Council, http://www.gwec.net/publications/global-wind-report-2/global-wind-report-2015-annual-market-update/ [06/05/2016].

Gorsevski, P. V., Cathcart S. C., Mirzaei, G., Jamali, M. M., Ye, X. & Gomezdelcampo, E., 2013. ‘A group-based spatial decision support system for wind farm site selection in Northwest Ohio’. *Energy Policy*, vol. 55, pp. 374-385.

Hansen, H. S., 2005. ‘GIS-based Multi-Criteria Analysis of Wind Farm Development’. In Hauska, H. & Tveite, H. (eds.), ScanGis 2005: *Proceedings of the 10th Scandinavian Research Conference on Geographical Information Science,* pp. 75-87. Department of Planning and Environment.

Herbert, G.M. J., Iniyan, S., Sreevalsan, E. & Rajapandian, S., 2007. ‘A review of wind energy technologies.’ *Renewable and Sustainable Energy Reviews*, vol. 11, pp. 1117-1145.

Intergovernmental Panel on Climate Change, 2013. ‘Summary for Policymakers’, In: *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker,T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jäger-Waldau, A. & Ossenbrink, H., 2004. ‘Progress of electricity from biomass, wind and photovoltaics in the European Union.’ *Renewable and Sustainable Energy Reviews*, vol. 8, pp. 157-182.

Krohn, S. (ed.), 2009. The Economics of Wind Energy - A report by the European Wind Energy Association. European Wind Energy Association, http://www.ewea.org/fileadmin/files/library/publications/reports/Economics_of_Wind_Energy.pdf [05/04/2016].

Latinopoulos, D. & Kechagia, K., 2015. ‘A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece’, *Renewable Energy*, vol. 78, pp. 550-560.

Longley, P. A., Goodchild, M. F., Maguire, D. J. & Rhind, D. W., 2011. *Geographic Information Systems & Science*. 3rd edition, John Wiley & Sons, Inc, Hoboken, United States of America.

Lymburner L., Tan P., Mueller N., Thackway R., Lewis A., Thankappan M., Randall L., Islam A., and Senarath U., 2010. *250 metre Dynamic Land Cover Dataset (1st Edition)*. Geoscience Australia, Canberra, Australian Government, http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_a05f7893-0031-7506-e044-00144fdd4fa6/The+National+Dynamic+Land+Cover+Dataset [19/03/2016].

Malczewski, J., 2000. ‘Review Article: On the Use of Weighted Linear Combination Method in GIS: Common and Best Practice Approaches.’ *Transactions in GIS*, vol. 4, pp. 5-22

Malczewski, J., 2006. 'GIS-based multicriteria decision analysis: a survey of the literature.' *International Journal of Geographical Information Systems*, vol. 20, pp. 703-726.

Malczewski, J. & Rinner, C., 2015. *Advances in Geographical Information Science*. Springer Science + Business Media, New York, United States of America.

Navigant Research, 2015. Executive Summary: World Wind Energy Market Update 2015, International Wind Energy Development: 2015-2019. Navigant Research, Chicago, USA.

Nelson, V., 2013. *Wind Energy, Renewable Energy and the Environment*, 2nd edition, CRC Press, Boca Raton, United States of America.

Next 10, 2015. *2015 California Green Innovation Index, International Edition.* Next 10, http://next10.org/sites/next10.org/files/2015-Green-Innovation-Index.pdf [03/03/2016].

Office of Environment & Heritage, 2010. *Critical Habitat Declaration.* Office of Environment & Heritage, Parramatta, NSW Government, http://mapdata.environment.nsw.gov.au/geonetwork/srv/en/metadata.show?id=477&currTab=simple [15/03/2016].

Office of Environment & Heritage, 2015a. *Map of Critically Endangered Ecological Communities NSW Version 3.* Office of Environment & Heritage, Parramatta, NSW Government, http://mapdata.environment.nsw.gov.au/geonetwork/srv/en/metadata.show?id=783&currTab=simple [15/03/2016].

Office of Environment & Heritage, 2015b. *NSW National Parks and Wildlife Services (NPWS) Estate.* Office of Environment & Heritage, Parramatta, NSW Government, http://mapdata.environment.nsw.gov.au/geonetwork/srv/en/metadata.show?uuid=%7b3F9E78BC-2F56-452A-A37F-B216B31C76CA%7d [15/03/2016].

Office of Environment & Heritage, 2015c. *State Heritage Register – Curtilages.* Office of Environment & Heritage, Parramatta, NSW Government, http://mapdata.environment.nsw.gov.au/geonetwork/srv/en/metadata.show?id=627&currTab=simple [16/05/2016].

Office of Environment & Heritage, 2016. *The Regional Clean Energy Program.* Office of Environment & Heritage, NSW Government, http://www.environment.nsw.gov.au/communities/clean-energy.htm [23/10/2016].

Pohekar, S. & Ramachandran, M., 2004. 'Application of multi-criteria decision making to sustainable energy planning - a review.' *Renewable and Sustainable Energy Reviews,* vol. 8, pp. 365-381.

Saaty, R. W., 1987. 'The analytic hierarchy process – what it is and how it is used.' *Mathl Modelling*, vol. 9, pp. 161-176.

Short, T. A., 2004. *Electric Power Distribution Handbook*. Grigsby, L. L. (ed.). CRC Press LLC, Boca Raton, United States of America, https://goodboygunawan.files.wordpress.com/2010/03/electric-power-distribution-handbook.pdf [02/02/2017].

Siraj, S., Mikhailov, L. & Keane, J. A., 2015. 'PriEsT: an interactive decision support tool to estimate priorities from pairwise comparison judgments.' *International Transactions in Operational Research*, vol. 22, pp. 217–235.

Spatial Services, 2016a. *GDA*. Spatial Services, Bathurst, NSW Government, http://spatialservices.finance.nsw.gov.au/surveying/geodesy/gda [02/11/2016].

Spatial Services, 2016b. Map projections. Spatial Services, Bathurst, NSW Government, http://spatialservices.finance.nsw.gov.au/surveying/geodesy/projections [02/11/2016].

Sundström, T. & Rydén, L., 2003. 'The Prospect of Sustainable Development', in Rydén, L., Migula, P. & Andersson, M. (eds.), *Environmental Science*, The Baltic University Press, Uppsala, Sweden.

Sustainable Energy Development Authority, 2001. *NSW Wind Energy Handbook 2002*. Sustainable Energy Development Authority, Sydney, NSW Government.

Tegou, L., Polatidis, H., Haralambopoulos, D., 2010. 'Environmental management framework for wind farm siting: Methodology and case study'. *Journal of Environmental Management*, vol. 91, pp. 2134-2147.

Van Haaren, R. & Fthenakis, M., 2011. 'GIS-based wind farm site selection using spatial multi-criteria analysis (SMCDA): Evaluating the case for New York State', *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 3332-3340.

Van Lier, H., 1998. 'The role of land-use planning in sustainable rural systems'. *Landscape and Urban Planning*, vol. 41, pp. 83-91.

Wade, S.L., Barry, C.M. & Nelson, M.D. (compilers), 2016. *Renewable energy map of New South Wales, Version 1 (Digital Dataset)*. Geological Survey of New South Wales, Maitland, Australia, https://search.geoscience.nsw.gov.au/product/9197 [13/09/2016].

Watson, J. J.W. & Hudson, M. D., 2015. 'Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation.' *Landscape and Urban Planning*, vol. 138, pp. 20-31.

Wiser, R., Yang, Z., Hand, M., Hohmeyer, O., Infield, D., Jensen, P. H., Nikolaev, V., O'Malley, M., Sinden, G. & Zervos, A., 2011. 'Wind Energy'. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., & von Stechow, C. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

World Commission on Environment and Development, 1987. *Report of the World Commission on Environment and Development: Our Common Future.* World Commission on Environment and Development A/42/427, Geneva, Switzerland, http://www.un-documents.net/wced-ocf.htm [04/03/2016].

Zadeh, L., 1965. 'Fuzzy Sets'*. Information and Control*, vol. 8, pp. 338-353.

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