Assessing the Wind and Solar Energy Potential of the Isle of Man

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Abstract

Climate change and energy security pose fundamental threats to the planet and humanity, with island communities particularly vulnerable. Renewable energy has significant potential to mitigate these threats, however, in the Isle of Man (IOM), renewable developments are lacking. Despite receiving greater attention in recent years there remains limited research into the renewable energy suitability of the island or its generation potential. This study assesses the potential of wind and solar energy – two of the most viable renewable technologies – for development on the IOM. A critical aspect of renewable planning and site selection is finding a balance between technical, social, environmental, economic and political factors. A holistic approach that combines geographic information systems (GIS) with multi-criteria decision analysis (MCDA) is used to evaluate the suitability of the IOM for renewable development based on these factors, a novel study for this area. The results obtained highlight the high potential of the island for wind and solar energy, with 22.9% of the island suitable for onshore wind and 27.2% suitable for solar development. Wind energy potential appears higher, with 8.5% of the island deemed highly suitable, compared with 2.3% for solar energy. Analysis indicates that the planned offshore wind farm in the Irish Sea is located optimally. Estimates also suggest onshore wind, offshore wind and solar energy could all individually exceed the energy demand requirements of the island. Findings are highly relevant for informing energy development plans and island policies, and also highlight that the global potential of renewable energy is realised in the IOM. Furthermore, the GIS-MCDA approach is tested in a proof-of-concept manner, with the validity and reliability verified through comparisons with other literature and existing research. Additionally, limitations of the study are highlighted whilst opportunities for further research to complement and build on the findings are identified.

Key words

Wind energy; solar energy; geographic information systems; multi-criteria decision analysis; site selection; Isle of Man.

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Disclaimer by Manx Utilities (14/07/23) to allow publication:

"Overall Manx Utilities is of the opinion that this is an excellent piece of work for a University dissertation for a highly complex topic and has given good consideration to a variety of constraints which impact on the deliverability of renewables. Manx Utilities has taken on-board specialist consultant, Wardell-Armstrong to carry out a detailed appraisal of sites suitable for renewables on the Isle of Man and will be moving to develop renewables on Island over the next three years. The consultant has had access to more detailed information than was made available to Ben.

In addition to the study limitations outlined in Section 5.4, further work would be required before this piece of high-level work can be utilised for the development of renewables on the Isle of Man, including:

1) *The limitations of the network in terms of where renewable generators could be connected. The WSP report has highlighted that under certain fault conditions renewable generators would be limited in localised areas of the network.*
2) *The stability of the power system as a result of introducing varying levels of renewables onto the system.*
3) *Detailed analysis of protected heathland habitat and the impact on the sites identified in the AEA (2010) report. Data constraints meant that the latest heathland habitat mapping was unavailable for this piece of work, and development is restricted by the high biodiversity potential (as referenced in the MCDA weightings).*

A review of these three areas would make for a good follow-up study or separate dissertation from another student at a later date."

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List of abbreviations

Abbreviation	Definition
AHP	Analytic Hierarchy Process
ASSI	Area of Special Scientific Interest
dB	Decibel
DSM	Digital surface model
DTM	Digital terrain model
GHI	Global horizontal irradiance
GIS	Geographic Information System
GW	Gigawatt
GWA	Global Wind Atlas
Hz	Hertz
IOM	Isle of Man
kV	Kilovolt
$kWhm^{-2}$	Kilowatt hours per square metre
LCOE	Levelised cost of electricity
LiDAR	Light Detection and Ranging
MCDA	Multi-criteria decision analysis
MW	Megawatt
NIMBY	Not-in-my-back-yard
nm	Nautical miles
PROW	Public Right of Way (also referred to as footpaths)
PVOUT	Solar potential
R^2	Coefficient of determination
Solar PV	Solar photovoltaic
TT (course)	Tourist Trophy motorcycle road racing event
UK	United Kingdom

1. Introduction

Climate change presents a significant threat to humanity and planet biodiversity and is regarded as the defining crisis of our time (WHO, 2021; UN, 2023a). Impacts are widespread, rapid and catastrophic, and evidence affirms that anthropogenic activity has unequivocally caused global warming (IPCC, 2023). Greenhouse gas emissions and increasing atmospheric carbon dioxide concentrations are primary drivers, with 88% of global carbon dioxide emissions derived from fossil fuels (Olivier, 2022). Despite rapidly declining finite resources, fossil fuels supplied 82% of global energy consumption in 2021 (Kalair et al., 2021; BP, 2022). Thus, coinciding with increasing energy demand, the reliance on fossil fuels poses a fundamental threat to energy security (IEA, 2022a). Russia's invasion of Ukraine compounded concerns, triggering a global energy crisis with surging costs and fractured supply chains, forcing energy security to the forefront of the political agenda; especially for nations relying on volatile imported energy (Dillon & Mawhood, 2022; Zakeri et al., 2022; IEA, 2023a).

A transition to cleaner energy is therefore required, with energy security concerns and climate pledges (such as the Paris Agreement) key driving forces (IRENA, 2020; Berdysheva & Ikonnikova, 2021; IEA, 2023a). In theory, renewable energy resources can exponentially exceed global energy demand, meaning their potential is extremely high (Ellabban et al., 2014; Twidell, 2021). Globally, renewables contributed to 29% of electricity generation in 2020, with wind energy and solar photovoltaic (PV) energy projected to contribute to two-thirds of near-future renewable growth (IEA, 2021a). Global renewable capacity is forecast to increase by 75% (2,400 GW) between 2022-2027, with China responsible for almost half of this growth, despite reducing wind and solar enabling regulations (such as feed-in tariffs) as a result of their increasing cost-competitiveness (Olabi & Abdelkareem, 2022; Zhao et al., 2022; IEA, 2023b). Wind energy, solar PV, hydropower and bioenergy are the four greatest contributors towards global renewable energy generation (over 90% of total generation), and are generally the most viable technologies (IEA, 2021b; BP, 2022; Ritchie et al., 2022). Thus, renewable energy has the potential to mitigate climate change and stabilise fragile energy securities. However, the installation of renewable energy is not straightforward and requires a delicate balance of elements. A critical aspect of renewable development relates to site selection, which involves a complex planning process that must encapsulate technical, social, environmental, economic and political factors (Bennui et al., 2007). As proven by numerous studies, merging geographic information systems (GIS) with multi-criteria decision analysis (MCDA) is an effective method of facilitating this spatial planning, enabling evaluation of the suitability of an area for renewable installation (Höfer et al., 2016; Shao et al., 2020).

The Isle of Man (IOM), an island in the British Isles, imports 92% of its energy and currently has a negligible amount of installed renewable capacity (IOM Government, 2021). Progress is underway, with recent economic strategies and climate change plans targeting 75% renewable energy by 2035, net zero emissions by 2050 and greater investment in a 'green economy' (IOM Government 2022a; 2022b). However, a challenge is to maintain the affordability of energy for customers; therefore, a more cost-effective pathway was chosen, involving importing the majority of clean energy, rather than installing on-island capacity (*ibid.*). Consequently, concerns over energy security remain; exacerbated by Great Britain's ongoing energy crisis (Curran, 2019; Milne, 2022). Research is lacking on the renewable energy potential of the IOM; this study aims to fill this knowledge gap and build upon previous research by using GIS-MCDA site selection evaluation to assess the potential of wind and solar energy on the IOM. Findings will provide a novel insight into the overall suitability of the island, its energy generation potential, and will validate the GIS-MCDA method through a proof-of-concept manner. Thus, the three key research objectives are:
1) To evaluate the suitability of the IOM for wind energy generation;
2) To evaluate the suitability of the IOM for solar energy generation;
3) To examine the wind and solar energy generation potential of the IOM.

Following this introductory section, this study will review key literature to assess the current viability of different renewable energy sources, the theory and importance of various site selection criteria, and the most effective methodological approaches for studies of this nature. The methodology section describes the data collection process and the framework used to address each objective before the results are presented in section four. A detailed discussion follows, structured by research objective, to evaluate, compare and validate findings from this study with existing literature and empirical data. Findings will be used to assess the strengths and weaknesses of the GIS-MCDA approach and the study limitations. The study concludes with a summary of the main findings, areas of improvement and areas for future research.

2. Literature Review

2.1 The state of renewable energy

The utilisation of renewable energy varies by country, depending on the abundance of natural resources and an array of social, political and economic factors that both enhance and hinder development (Gross et al., 2003; Osunmuyiwa & Kalfagianni, 2017). Wind energy is viable due to its rapid growth and rising load factors (energy productivity; 34-43% in 2018, increasing to up to 60% by 2050 (IRENA, 2019)), driven partly by increasing turbine sizes which generally produce more energy (Dröes & Koster, 2021). However, growth needs to quadruple by 2030 to stay on course for a 1.5ºC climate warming pathway (GWEC, 2022). The levelised cost of electricity (LCOE; the average cost per unit of electricity generated during a plant's lifetime) of wind declined by 15% (onshore) and 13% (offshore) between 2020-2021, with costs expected to reduce by 37-49% by 2050 (BEIS, 2020; Wiser et al., 2021; IRENA, 2022). However, noise/visual pollution, intermittency and bird strikes are among the drawbacks (Wang & Wang, 2015; Kirchoff et al., 2022). Additionally, the impacts of climate change on wind energy are uncertain, with declines or increases in potential possible (Greene et al., 2010; Zeng et al., 2019); or a spatial mix of both (Carvalho et al., 2017; Cronin et al., 2018). Whilst modelling uncertainties caveat projections, climate change impacts on solar PV are forecast to be minor (Gernaat et al., 2021; Yang et al., 2022). Despite variance in irradiance, significant solar generation is possible globally (UN, 2023b). Large-scale (grid-supplying) solar PV is modular (flexible capacity) and currently the least expensive electricity generation option, highlighting its viability (Ellabban et al., 2014; IEA, 2023b). However, despite its growth, solar PV suffers from insolation intermittency, cloud cover, air pollution and soiling (e.g., from dust) reducing performance, and a relatively low load factor of 10-21% (Meghami et al., 2016; Li et al., 2017; IEA, 2018; Allouhi et al., 2022).

Hydropower is an established technology (Breeze, 2018), and its relatively high efficiency, 50% load factor, and energy conversion density result in an economical and generally reliable resource (IRENA, 2015; Erinofiardi et al., 2017; Li et al., 2018). However, large-scale hydropower is associated with issues including high initial costs, ecosystem disturbance and disruption to livelihoods (Nautiyal et al., 2011). Small-scale hydropower is viable in some cases, although this technology still features harmful impacts and is more suited to decentralised systems and small communities (Hoffken et al., 2014; Manders et al., 2016; Yah et al., 2017). Furthermore, hydropower is subject to the cascade of uncertainties of a changing climate, with droughts and retreating glaciers further threatening the security of the resource (Sorg et al., 2012; Wilby et al., 2014; van Vliet et al., 2016; Wilby, 2017).

Other notable renewable technologies include geothermal, marine energy and bioenergy. Geothermal energy LCOE can compete with solar, wind and hydropower, however, its global viability is restricted by the geological conditions needed (Barbier, 2002; Soltani et al., 2021). Marine energy potential (waves, tidal, currents, thermal energy conversion and salinity gradients) is predicted to exceed future energy demand (particularly for islands) however, the LCOE for current prototypes are significantly higher than other sources due to the relative infancy of the technology, hindering its viability (Ellabban et al., 2014; Chowdhury et al., 2021). Bioenergy usage has increased by 7% per year since 2021 and is projected to continue rising (IEA, 2022b). Intermittent technologies (e.g., wind and solar) will require additional dispatchable (on-demand) generation; highlighting a significant benefit of bioenergy, in addition to its ability to grow in heterogeneous conditions (Ellabban et al., 2014; Sivabalan et al., 2021; IEA, 2023b). Inefficiencies, large spatial requirements, and higher LCOEs hinder its progress (Tun et al., 2019; BEIS, 2020; Sivabalan et al., 2021). Other emerging sources may have future potential (e.g., concentrating solar power (CSP)), but technological immaturity and high costs inhibit present viability (Hussain et al., 2017; Boretti, 2018; Islam et al., 2018; Wilberforce et al., 2019).

In the UK, usage of renewable energy is rapidly increasing, accounting for 2% of energy generation in 1991, 14.6% in 2013 and 43% in 2020; greater than the European Union’s (21.8% in 2021 (Eurostat, 2023)) and placing the UK amongst the world’s leading countries (National Grid, 2023a; Fig. 1a). Wind is the dominant source (26.8% in 2022), with bioenergy (5.2%), solar power (4.4%) and hydropower (1.8%) the other main sources (*ibid.*). Despite this expansion, there has effectively been an onshore wind moratorium since 2015 due to a government policy that allows a single local objection to block a proposed development, resulting in the installation of just 16 onshore turbines between 2016-2020 (a 96% decline) and highlighting the intrinsic relationship between energy, politics, economics and social factors (Harper et al., 2019; Carter & Little, 2021; Pickard, 2022). Discontinuation of feed-in-tariffs further hindered development, although as China shows, these revenue incentives are becoming increasingly insignificant (Hannon et al., 2021; Zhao et al., 2022).

The renewable energy potential of the IOM could be expected to be similar to the UK given the similar climate. However, hydropower is excluded as a viable source of large-scale generation due to insufficient rainfall with the small landmass (572 km^2) (Manx Utilities, *pers. comm.*); the hydropower station at the largest reservoir (Sulby) contributes < 1% to total generation (IOM Government, 2021; Fig. 1b). Bioenergy is restricted by land availability and resources, with an estimated potential of 131 MW, including imports (*ibid.*). On the other hand, wind and solar energy are viable options but there are no large-scale developments of either (AEA, 2010; Curran, 2019). Renewable development potential is high, and whilst increasing renewable installation is important, selecting appropriate sites for development is also crucial.

2.2 Wind and solar energy site selection

Selecting suitable sites for development is a multi-disciplinary exercise, involving a balance of social, political, economic, technical and environmental factors (Bennui et al., 2007; Anderson, 2020). The potentially adverse and multi-sensory effects of wind turbines on public health are reasons for exclusion (Palmer, 2018). Shadow flicker (a flickering effect of rotating blades in particular sunlight) is correlated with seizures, photosensitive epilepsy and general irritation, with the rotation frequency within the disturbance range (2.5-40 Hz) (Verkuijlen & Westra, 1984; Clarke, 1991; Harding et al., 2008). Evidence suggests seizure risk does not significantly reduce until 4 km away, exacerbating the issue, although the 25% atmospheric attenuation of light per km should proportionally reduce this risk (Curcio et al., 1953; Binnie et al., 2003; Harding et al., 2008). Modelling can predict the hazard; for example, Haac et al. (2022) found over 50% of studied homes within 500 m of a turbine suffered from flicker, contrasting evidence suggesting flicker frequency does not cause significant harm (but may still be a nuisance), and only one case was identified in the UK (PB, 2011); although different flicker definitions and methodologies reduce comparability.

Turbine noise pollution may cause adverse health impacts within 1.4-2 km and where levels exceed 45 dB (a similar threshold to recommended aircraft noise limits (WHO, 2018); the most disruptive noise (Miedema & Oudshoorn, 2001)), reducing quality of life and influencing sleep and annoyance (Janssen et al., 2011; Shepard et al., 2011; Nissembaum et al., 2012). However, limited sample sizes, weak relationships, a lack of correlation coefficients, and a statistically insignificant deviation from the general population caveat these findings (Ollson et al., 2013; Barnard, 2013; Knopper et al., 2014). Mroczek et al. (2012) found no correlation between proximity to turbines and quality of life, although other factors such as income, subjectivity and topography may skew results, whilst annoyance is strongly correlated to the perceived visual impact (Pederson, 2009; Evans & Cooper, 2012; Knopper et al., 2014). Turbine electromagnetism levels are not of concern (Israel et al., 2011; McCallum et al., 2014). Ice throw and turbine failure are risks (particularly in colder and windier climates), however, the majority of risk is associated with worker safety during construction/maintenance, and not public health (Asian et al., 2017; Rastayesh et al., 2019; Szász et al., 2019; Katsaprakakis et al., 2021). Nevertheless, safety separation distances (e.g., from roads, footpaths and airports) can minimise risks. Adverse health impacts from solar PV are minimal. In fact, both technologies are likely to increase overall health by replacing pollutant-intensive sources of energy (e.g., coal or gas), thus improving air, water and soil quality (Adgate et al., 2014; Prehoda & Pearce, 2017; Yang et al., 2018; Hendryx et al., 2020). Furthermore, a nocebo effect is observable for many wind/solar-derived health complaints (Chapman et al., 2013).

Social acceptance is critical for renewable energy progression. Global and local scale attitudes towards development differ; whilst generally supported, local attitudes – including 'NIMBYism' (not-in-my-back-yard syndrome) – are barriers to development (Bell et al., 2005; van der Horst, 2007). Attachment to the environment exacerbates barriers, and opposition is often derived from the perceived visual impact, in addition to health fears (Devine-Wright & Howes, 2010; Höfer et al., 2016). Justice in spatial planning is key for policymakers to appease communities (Hall et al., 2013). Thus, whilst social acceptance can be improved with fair public consultations, effective communication and by providing community benefits (Gross, 2007; Walker et al., 2014), low-value land away from settlements and attractions is likely to be favourable for development. These social issues must also be considered through a political lens, often requiring a compromise to balance social demand with policies, targets for environmental progression (e.g., net zero by 2050 and the Paris Agreement) and financial obstacles (Yi & Feiock, 2014; Arantegui & Jäger-Waldau, 2018).

Costs of installation vary spatially. Proximity to road and electricity networks reduces costs and electricity losses whilst increasing accessibility, and high-value land (e.g., prime agricultural) should be avoided; in contrast, government-owned land should reduce costs (Tegou et al., 2010; Höfer et al., 2016). Hence, financial factors affect site selection; their omission in wind siting studies by Rodman & Meentemeyer (2006) and Bennui et al. (2007) highlight limitations to their findings. Site selection is predominantly driven by technical characteristics of the land: wind energy (e.g., speed, frequency, density and turbulence), solar irradiance, slope (steep slopes are usually avoided for technical and financial reasons), and aspect (for solar) (Tegou et al., 2010; Watson & Hudson, 2015; Höfer et al., 2016; Kereush & Perovych, 2017). However, there is variance in the application of criteria between studies, both in their relative importance and in the ranges defined as suitable, introducing elements of subjectivity and inconsistent variables that caveat findings and restrict comparability.

The environmental impact of turbines often relates to bird and bat strikes. Zimmerling et al. (2013) estimated an average mortality rate of 8 birds per turbine per year, although rates are difficult to estimate (Smallwood et al., 2007). The increasing size of turbines may increase this threat (turbine diameter has grown by 34% since 2013 (Hartman, 2022)), although the rate is significantly lower than other anthropogenic sources (e.g., building and power line collisions) (Loss et al., 2015; Choi et al., 2020). Solar PV impacts are generally limited to earlier stages of the supply chain (Hamed & Alshare, 2022), however, land clearance, soil erosion and habitat loss degrade the environment (Hernandez et al., 2014; Aman et al., 2015; Nazir et al., 2020); impacts of both wind and solar energy, thus siting must use an environmental exclusion zone.

2.3 Methodological approaches

Spatial analysis is underpinned by 3D modelling of topography. Digital terrain/surface models (DTMs (bare earth surface features) and DSMs (surface with built and natural features)), derived from LiDAR mapping, are high-resolution models that enable detailed spatial analysis (e.g., slope and aspect) (Chen et al., 2017). Crucially, topographic models also enhance wind/solar models. The Global Wind Atlas (GWA) produces mean wind flow models by combining microscale data (topographic models accounting for airflow complexities over undulating surfaces) with mesoscale atmospheric reanalysis of climatic patterns in a downscaling process (GWA, 2021).

The reanalysis enables a significant improvement in spatial resolution; improving the resolution of two major wind power simulation tools, ERA5 (31 km) and MERRA-2 (50 km), to 250 m in a validated approach (Gruber et al., 2019; 2022). However, GWA models are limited by strong mesoscale forcing and by complex and steep topography (Mortensen et al., 2017). Coarse input resolution, terrain biases and noise also contribute towards uncertainties of wind energy estimations (Davidson & Millstein, 2022); therefore, the GWA only offers an insight into wind potential and is not a definitive model. Likewise, the Global Solar Atlas model (250-1,000 m variable spatial resolution) suffers from similar limitations, with ±8% uncertainty for high latitudes (> 50º) and coastal zones (< 15 km), while the UK only features two high-quality ground measurement validation samples (ESMAP, 2019).

The efficient organisation, storage, manipulation and display of geographically referenced information make GIS a powerful spatial analysis tool (Dangermond, 1992; Rikalovic et al., 2014). Its popularity in site selection is due to its competency in solving complex planning issues (Bennui et al., 2007; Carrión et al., 2008a, cited in Tegou et al., 2010). An exclusion zone approach for site selection does not differentiate between suitable sites, assuming all inclusion areas are suitable, however, in reality, areas away from urban and environmental sites are likely to be more accepted (Höfer et al., 2016). MCDA implements a logical framework that evaluates the suitability of potential sites based on a range of criteria (Malczewski, 1999; Ananda & Herath, 2009; *ibid.*). Different methods of MCDA – discrete (value-utility functions, distance-based and outranking techniques) and continuous (mathematical and heuristic models) – are used in different contexts, however, the Analytic Hierarchy Process (AHP), a discrete pairwise comparison method, is the most popular technique in sustainable energy planning (Pohekar & Ramachandran, 2004; Gebre et al., 2021). Developed by Saaty (1980), the AHP method is flexible and easily implemented, working by ranking attributes in pairs to assess their relative importance (Tegou et al., 2010). This systematic approach quantifies the subjective importance of each criterion and has been tested and validated extensively in renewable planning (Höfer et al., 2016; Ali et al., 2018; Koc et al., 2019; Colak et al., 2020; Shao et al., 2020). The requirement of subjective inputs (for importance weightings) could be viewed as a drawback, however, given the subjective nature of planning (especially with a current lack of legislation), the AHP method stands out.

3. Methodology

3.1 Study site

The IOM (572 km^2), located in the Irish Sea between England and Northern Ireland, is a self-governed British Crown dependency with a population of 84,000, spanning 53 km from north to south and a maximum of 22 km from east to west (Fig. 2a; IOM Government, 2022c). 63% of the population reside in the capital, Douglas, and three coastal towns (Ramsey, Peel and Castletown) with the south-west and centre of the island characterised by relatively sparsely populated hilly terrain; 75% of the island is used for agriculture (IOM Government, 2015). The island features a rich cultural history, with many landmarks and historical sites on offer. Furthermore, in 2016, the island became a designated UNESCO Biosphere Reserve in recognition of its natural environment and sustainable development, becoming the first entire nation to hold the status (Biosphere, 2023; UNESCO, 2023). Consequently, it is critical that any renewable energy developments must consider and respect these elements.

The island has a temperate oceanic climate (based on the Köppen (1936) climate classification), averaging 883 mm of rainfall annually (up to 1,900 mm over the central hills) and 1,651 hours of sunshine (Met Office, 2023). Therefore, the island receives, on average, less rainfall and more sunshine than northern England (986 mm, 1,433 hours) and the UK (1,163 mm, 1,402 hours), although the IOM only has one official weather station (Ronaldsway Airport, located in a low-lying and relatively dry area) meaning data validation is limited (*ibid.*). The annual mean global horizontal irradiance (GHI) is 993.6 $kWhm^{-2}$ (SolarGIS, 2022). Average wind speeds at 50 m height are 8.04 ms^{-1} over the island and 9.29 ms^{-1} over the Irish Sea (GWA, 2021), with a south-westerly prevailing wind direction (Fig. 2b). The energy potential of the island and its surrounding 12 nautical miles (nm) of Irish Sea territory will be studied.

3.2 Datasets and data collection

The GIS-based spatial analysis was conducted using ESRI ArcMap 10.8.1 (although the framework can be tested using any GIS software with overlay capabilities (Tegou et al., 2010)), utilising a range of secondary data (Table 1) and ArcMap analysis tools (Table 2 describes each tool). UK guidance advises calculating mean wind speeds at 45 m above ground level (CSE, 2016), however, this data is unavailable; mean wind speed at 50 m is used instead. Using the standardised measurement increases relevancy and comparability, despite modern wind turbine hub heights exceeding this height; the 2021 US average was 94 m (Hartman, 2022). Some data required georeferencing into feature class format within ArcMap, although this can introduce spatial uncertainty (McEachern & Niessen, 2009). The *create signatures* and *maximum likelihood classification* ArcMap tools partially assisted with georeferencing and digitisation, by automatically classifying highly contrasting colours on the environmental dataset source image. Railways and urban areas were digitised from satellite imagery (also an erroneous process (Heuvelink, 2005)) to resolve insufficient data, although the urban classification is subjective. Suitable electricity transmission networks (11kV and 33kV; commonly used to connect turbines in a local grid (Molina & Mercado, 2011; Thyssen, 2015)) were extracted from the electricity dataset.

3.3 Methodological framework

The GIS-based site selection process for both onshore wind and solar PV requires a sequence of steps that account for both the exclusion (restricted) and inclusion (evaluation) areas of the IOM. The evaluation of inclusion areas requires MCDA to enable the consideration of variable weightings for each criterion; the AHP method of MCDA is used, with its suitability highlighted by its popularity in energy planning. To solve the lack of island-specific expert opinion (determining criteria importance), wind weighting values are adapted from Höfer et al. (2016), placing a greater emphasis on environmental and social factors; aligning closely with the values of the IOM. Solar PV criteria literature is more consistent, thus approximate averages are taken. Rated and restricted areas are then consolidated to form the final site suitability map; Fig. 3 summarises the key steps of the framework. Offshore wind site analysis will not use MCDA; instead, an existing planned site will be evaluated. Site suitability mapping contributes towards objectives 1 and 2 and enables analysis into objective 3.

3.3.1. Onshore wind and solar PV. 12 onshore wind criteria were excluded, with Table 3 providing a summary of the criteria. Exclusion areas are based on Boolean (algebraic) logic, which reduces values (areas) to either true or false, based on their suitability (Cheng & Thompson, 2016). Slope percentage was derived from the IOM DTM using the *slope* tool. The 5 m DTM has a coarser resolution than the 2 m DSM, which would unnecessarily include features such as hedgerows and boundary walls. The *raster calculator* tool was used to conditionally remove slopes > 30%, deemed too steep for wind turbines, and also to remove wind speed values < 5 ms^{-1} at 50 m (the minimum threshold for turbine operation). The *buffer* tool created separation distances around the 10 applicable criteria (Table 3), defining the 'non-buildable' zone (Yee, 2018). The *raster to polygon* tool standardised the formats of any non-shapefile outputs. Hence, the criteria can be directly layered and visualised, unlike Höfer et al. (2016), who use the *cell statistics* tool to combine their raster datasets.

The exclusion process for large-scale solar PV is similar, using the 11 criteria listed in Table 4 instead. Slope direction was derived from the IOM DTM using the *aspect* tool; however, the 5 m resolution is too high for the purpose. Flatter areas can cause unnecessary complexity and noise in the aspect output (Chang & Tsai, 1991), excluding marginally north-facing slopes due to minor slope angles and negligible topographic undulations. Therefore, the *focal statistics* tool was used to smooth the DTM raster, before the *raster calculator* conditionally removed N/NE/NW-facing slopes, as well as slopes > 15%. Urban areas and water bodies have been excluded from analysis as small-scale and floating solar PV are not in the scope of this study, with existing literature examining these (BV, 2022). The initial output contained land areas < 50 acres (insufficient for large-scale solar PV (Rees, 2023)). The *explode multipart feature* tool was used in conjunction with *calculate geometry* to highlight and remove these below-threshold areas (although adjacent polygons – separated by an overhead transmission line – that totalled > 50 acres were retained).

Following the AHP method, 10 onshore wind inclusion criteria were weighted by importance (Table 3), allowing for a spatial grading of locations (Höfer et al., 2016). The *Euclidean distance* tool was applied to each distance-based criterion before the *reclassify* tool standardised these outputs (in addition to the wind speed and slope angle criteria) based on the Table 5 value scores. Similarly, 9 solar PV inclusion criteria were weighted by importance (Table 4), before *Euclidean distance* and *reclassify* were used with the Table 6 value scores. Onshore wind and solar PV inclusion and exclusion areas were each then consolidated in accordance with AHP weights to produce a suitable area map. The *weighted overlay* tool could be used; however, it lacks support for missing values, rendering it incompatible with some data (Basharat et al., 2016; Höfer et al., 2016). *Raster calculator* was used instead as the criteria had already been reclassified into a 0-10 standardised scale, applying a map algebra expression that multiplied each inclusion criterion by the respective AHP weight; the sum generating an overall value score for each cell (Fig. 4; Yoon & Hwang, 1995; Tegou et al., 2010). The raster output lacks Boolean logic, meaning some exclusion areas were not scored 0. To solve this, *raster to polygon* was applied to preserve the resolution (the raster cells were of a lower spatial resolution) before the *merge, erase* and *clip* tools reapplied the exclusion areas to the suitability maps.

Considering the general optimal turbine placement of 3-5 rotor diameter separation in the crosswind direction and 8-12 rotor diameters in the prevailing direction enables a crude insight into research objective 3 (Patel, 2006). One method involves using the *generate tessellation tool,* but this fails to account for wind direction. Therefore, the *generate points along lines* tool was used to create a grid of transects both parallel and perpendicular to the prevailing wind direction (SW) at the mean placement interval (600 m and 1,500 m, assuming 150 m blade diameter); points created at intersections (via *feature vertices to points)* denote a wind turbine. After *clipping* to the inclusion areas, *buffers* identified any other suitable inclusion areas that a turbine was not clipped to; additional points were then manually added to these areas.

3.3.2 Offshore wind and further analyses. The *mosaic to new raster* and *extract by mask* tools prepared the wind speed raster for analysis of the Irish Sea. *Reclassify*, *raster calculator*, *raster to polygon* and *clip* were used to display the extent of area with lower wind speeds (< 9 ms^{-1} at 50 m). *Reclassify* also categorised bathymetry into 10 m intervals for simplicity, whilst *raster calculator* extracted vessel density values (> 0.8 average hours per km^2) to highlight popular shipping routes. With some additional layers, the suitability of the Irish Sea for offshore wind can be evaluated. Sensitivity analysis – validating results compared to the subjectivity of AHP weights (Meszaros & Rapcsak, 1996) – was conducted through *raster calculator*, modelling the effect of an equal weighting scenario and one that disregards visual impact (i.e., removing the urban and historical site buffers). Additional analysis was undertaken using the *zonal statistics* tool and Microsoft Excel, which was also used to analyse energy demand data and weather trends, contributing towards research objective 3.

4. Results

4.1 Wind energy (objective 1)

4.1.1 Onshore wind. The exclusion criteria (Table 3) restrict 441.3 km^2 of the IOM for onshore wind development (Fig. 5). Fig. 6 summarises the land excluded for each criterion. Road safety buffers are the most restrictive, excluding 46.6% of the IOM, which rises to 51.9% when combined with other safety criteria (footpaths, railway, electricity grid and the airport). Wind speed is the least restrictive; 99.8% of the island exceeds the 5 ms^{-1} threshold. Development is suitable in 130.7 km^2 (22.9%) of the IOM; this area is graded by combining each evaluation criterion (Fig. 7) with AHP analysis. Table 7 and Fig. 8 summarise and illustrate the suitable area, respectively. After AHP analysis, 36.9% (48.2 km^2) of the suitable area is highly suitable (> 8 value score), marginally less than the modal score of 7 (56.3 km^2; 9.8% of the island). Less than 0.1% score 10. The inclusion zone mean wind speed (8.3 ms^{-1}) is greater than the exclusion zone (7.9 ms^{-1}); both have standard deviations of 0.9 ms^{-1}. Lifting the slope constraint increases the suitable land area by 3.2% (20.7 km^2) to 26.1% (151.4 km^2), however, the mean inclusion zone wind speed remained the same (8.3 ms^{-1}).

The majority (52.9% (66.5 km^2)) of the suitable area is located around the central IOM hills (between Douglas, Peel and Ramsey). This area has a mean elevation of 237.5 m, over twice the island average (114.1 m), and a mean wind speed of 8.0 ms^{-1} (8.3 ms^{-1} in the inclusion zone). The island's southwestern hills (south of Peel) contain 18.7% (23.6 km^2) of the suitable area, with a mean elevation of 169.2 m and a wind speed of 8.2 ms^{-1} (8.6 ms^{-1} in the inclusion zone). Combined, these areas account for 71.6% of the total suitable area, and 71.3% of the total land with high suitability (scoring > 8). IOM wind speeds are generally highest around hill ridges and lowest in the valleys (Fig. 7a), and the rest of the island (mean elevation 53.2 m) has a mean wind speed of 8.0 ms^{-1}. All three potential sites identified in a more recent study are located in the suitable area identified in this study, with two scoring 8 in AHP analysis and one scoring 7 (BV, 2022). Six of the eight AEA (2010) sites are in the inclusion zone, with scores of 8, 8, 7, 7, 6 and 4. Overall, nine suitable sites have a mean score of 7. Table 7 also summarises the sensitivity analysis results. Equal weighting assigns each of the 10 onshore wind criteria a 10% weighting (Table 3). Relative to AHP analysis, the greatest changes are seen in the reduction (-7.6%) of land scoring 8 and the increase (+7%) in land scoring 6. The modal value remains 7 (46.5%). The no visual impact scenario increases the available area by 0.9% (5.7 km^2) and more evenly distributes value scores. Despite removing restrictive criteria, land scoring > 8 decreases by 19%, and a shift to lower scores is seen: relative to AHP, suitable area (%) for scores 5 and 6 increases 3-fold and 2-fold, respectively.

4.1.2 Offshore wind. Fig. 9 illustrates the current offshore wind situation of the IOM. Developments are restricted to the island's 12 nm territorial jurisdiction of the Irish Sea, whilst 9.0% of this area is occupied by environmental protection areas; all of which are within the 3 nm fisheries limit. Modelled wind speeds are < 9 ms^{-1} (at 50 m) in 9.9% of the 12 nm area; lower speeds are broadly contained within 1 nm of the IOM but extend further (up to 6 nm) towards the east of the island. Seafloor depth exceeds 60 m for 31.6% of the area, posing the greatest restriction on development. Depths between 50-60 m (8% of the 12 nm area) are generally found off the south, west and north coasts of the island, whereas depths < 30 m (26.4% of the area) outside the 6 nm limit are predominantly located off the east coast of the island. The planned offshore wind farm (184.6 km^2) is located in this shallower area (average depth -21.0 m, compared to -43.7 m for the whole 12 nm area) and features mean wind speeds of 9.1 ms^{-1}. To compare, the operational UK Irish Sea offshore wind farms (308.9 km^2) have mean wind speeds of 9.0 ms^{-1} and a mean depth of -25.5 m.

4.2 Large-scale solar PV energy (objective 2)

Table 4 exclusion criteria restrict 416.2 km^2 of the island for large-scale solar PV development (Fig. 10). Fig. 6 summarises the restrictions imposed by each criterion. Slope is the greatest restriction, excluding 32.3% of the IOM. Safety buffers (roads, footpaths, railways and the electricity grid) occupy a combined 5.0% (28.5 km^2); one-tenth of the onshore wind restriction. Consolidating the evaluation criteria (Fig. 11) creates the suitable area map (Fig. 12); Table 8 provides a value score breakdown. Development is suitable on 155.8 km^2 (27.2%) of land; 25.1 km^2 more than onshore wind. However, 8.5% (12.8 km^2) of the suitable area scores > 8 after AHP analysis, four times lower than onshore wind, indicating the potential of solar PV is lower. One of three land parcels scoring 9 is located at Ronaldsway Airport. The modal score is 6 (51 km^2; 8.8% of the IOM), whilst there is very little difference in the solar potential of the inclusion zone and the island mean (both score 8 in the PVOUT criterion).

To contrast the distribution of onshore wind, the majority (58.7% (95.1 km^2)) of suitable area is located in the flatter areas of the island (i.e., away from the central and southwestern hills), which feature the island's highest inclusion zone mean annual GHI value of 1,002.0 $kWhm^{-2}$. 73.6% of this area scores 7-9 in AHP analysis, whilst 90.3% of the total land area scoring > 8 is located in these areas. This correlates to solar irradiance, where the northern and southern plains receive greater exposure. Compared to onshore wind, the central hills contain less than half of the suitable area (24.5%), whilst also featuring a lower mean inclusion zone GHI value (990.9 $kWhm^{-2}$) than the southwestern hills (16.8% area, 999.5 $kWhm^{-2}$). The planned solar PV site scores 8 in AHP analysis (PCR, 2022), and the site is partially excluded by a designated wildlife zone buffer. A lack of officially identified sites limits further validation of the AHP method, whilst small-scale (and floating) projects have been omitted from this stage of analysis. The results of the sensitivity analyses are outlined in Table 8. Equal weights analysis assigns a weighting of 11.1% for each of the 9 criteria (Table 4), and despite the slight decline in land scoring > 8, there is an overall increase in land suitability, particularly in values 6 (+6.2%) and 7 (+8.5%). Disregarding visual impact results in a significantly greater amount of land available (213.5 km^2 (37.3%)) than AHP analysis, predominantly due to the removal of the urban buffer. Despite this increase, the distribution of suitability scores remains relatively unchanged from the AHP analysis. All analyses have modal scores of 6.

4.3 Energy generation estimates, island demand and climate (objective 3)

IOM suitable areas can accommodate a crude estimate of 214 turbines (assuming a 6 MW turbine with a 150 m rotor diameter), based on optimum turbine placement properties (Fig. 13). Multiplying rated capacity by 214 produces an absolute upper-bound estimation of 1,284 MW. Considering land value, 66 turbines could be located on land scoring > 8. Thus, high potential (> 8) land offers an upper-bound estimate of 396 MW. Applying a 27% load factor (Manx Utilities, *pers. comm.*) yields an output of 106.9 MW. The planned IOM offshore wind site had been projected to feature a capacity of 700-800 MW. However, modern turbine innovations continually raise the efficiency and output potential of the technology, meaning given the same area requirements, the generation capacity could be estimated to increase to 1,242 MW by utilising a prototype 15 MW Vestas next-generation turbine (with a rotor diameter of 236 m separated using Patel's (2006) optimal placement specifications; Vestas 2023a). A 40% load factor results in outputs of 280 MW and 496.8 MW, respectively. Curran (2019) estimates the IOM solar PV generation as 2.5 acres per MW. Dividing the suitable area (43,490.5 acres) by this generation potential gives an absolute upper-bound estimation of 17,396.2 MW. Considering land value scores reduces the total to 1,478.7 MW for land scoring > 8. Applying a load factor of 10% reduces output to 147.9 MW. A potential 15 MW floating array on Sulby reservoir and an initial 15 MW of solar PV sites on government-owned urban land have been sited (BV, 2022); these areas were omitted from analysis, so the totals can be added.

IOM average daily energy demand (Fig. 14a) peaks at 70.4 MW (winter 5-7 pm), with an average annual peak of 59.6 MW and overall mean of 46.2 MW. 30 MW baseload (minimum) generation is required, whilst winter demand is higher (Fig. 14b), peaking at 84.8 MW (12th Dec 2017). Wind speeds are highest during the winter (8.0 ms^{-1} peak; Fig. 15a), whilst summer features higher sunshine (daily mean 7.6 hours), fog (Fig. 15b) and temperatures (15ºC mean; Fig. 15c). Both annual sunshine (Fig. 15d) and mean temperature (Fig. 15e) have recorded statistically significant ($p < 0.05$) increases (6.4% and 10.1%, respectively) through time, when comparing averages from 1951-1980 (1,551 hours and 9.5ºC) and 1991-2020 (1,651 hours and 10.4ºC). Statistically significant ($p < 0.05$) relationships exist between energy demand and wind speed ($R^2 = 0.59$), sunshine ($R^2 = 0.79$) and temperature ($R^2 = 0.76$) with moderate to strong correlation, however, energy demand and rainfall exhibit an insignificant ($p > 0.05$) relationship with very weak correlation ($R^2 = 0.05$) (Fig. 16).

5. Discussion

This section is structured by objective, evaluating wind energy suitability, solar PV suitability, the generation potential of each, and will conclude with study limitations.

5.1 Evaluate the suitability of the IOM for wind energy generation (objective 1)

Since importance weightings were primarily derived from Höfer et al. (2016), their study of Aachen (707 km^2), Germany, is highly comparable, and the IOM's high potential is demonstrated with 22.9% of the island being suitable for onshore wind development, compared to Aachen's 9.4%. Therefore, differences are due to local context and buffer choice. 1.7% of Aachen is highly suitable, compared to 8.5% of the IOM (*ibid.*), although both areas record negligible 10 scores. The majority of the island's settlements are in low-lying areas, thus excluding large parts of these areas for health, safety and social reasons. In contrast, despite the emphasis on minimising visual impact, the urbanised areas of Aachen are more suitable, potentially due to the superimposition of desired criteria such as road and electricity networks, distance from environmental areas and flatter land (*ibid.)*. Höfer et al. (2016) omit a road safety buffer, despite the commonality of road exclusion zones (Latinopoulos & Kechagia, 2015; CSE, 2016; Ayodele et al., 2018), contributing towards the discrepancy. Upon review, buffer usage is contested. English legislation prefers a case-by-case analysis, deeming buffers inflexible and restrictive; Parliament has rejected attempts to legislate them (DCLG, 2013; BBLP, 2018). Thus, whilst local context is key, buffers remain valuable for pilot studies. The 500 m environmental buffer is relatively strict (BBLP, 2018; AECOM, 2022); coupled with the high AHP weighting, the UNESCO Biosphere status is respected. Heathland development is deterred, although turbines should not harm heathland ecology (Dorset, 2012).

Wind energy AHP scaling ranges between 6-7 ms^{-1} in Aachen, significantly lower than the range used for the IOM (5-11.75 ms^{-1}) (Höfer et al., 2016). This raises a limitation to AHP comparisons, as a value score of 8 (7 ms^{-1}) in Aachen corresponds with a score of 3 in this study (*ibid.)*, demonstrating the high wind energy potential of the IOM (99.8% of area > 5 ms^{-1}). Furthermore, Höfer et al. (2016) measure speed at 135 m height, rather than the 50 m height used in this study. Effects of this difference are derived from the wind speed power curve – a non-linear velocity increase with height – due to the effect of surface friction at the planetary boundary layer (Lange et al., 2002; Dragoi, 2013). A wind gradient is formed, resulting in significantly higher wind speeds at greater heights above ground level (Hadlock, 1998; Peña et al., 2016), with the boundary layer extending to 100-3,000 m (varying with time, location and weather) (Stull, 1988; Luo & Zhou, 2006). A 6 MW, 150 m diameter turbine has been used as standard (e.g., Vestas V150-6.0 MW™, tip height 200 m (Vestas, 2023b)), larger than the average onshore turbine (3 MW) to exploit the wind gradient and highlight the modern potential of innovative turbines (National Grid, 2023b). Load factors can increase by up to 9% between 80-160 m because turbine efficiency generally increases with height and larger blade diameters equate to larger swept areas (Mathew & Philip, 2011; Lantz et al., 2019; Smith & Griffin, 2019). The trend of increasing sizes highlights this, although turbine heights are often capped for socio-environmental reasons (SLC, 2019; National Grid, 2023b). However, there is a trade-off; taller turbines require larger safety buffers, reducing the suitable area (turbine height + 10%; derived from UK councils (DOENI, 2009; LUC, 2017; SCC, 2020)); safety is the dominant restriction in this study. Smaller turbines would increase the suitable area at the expense of energy output, although Araújo et al. (2021) suggest small-scale turbines, similar to small-scale hydropower, remain a viable alternative.

Considering wind energy is the most important criterion, areas with the lowest wind energy should correlate with low suitability scores, proven by Tegou et al. (2010), Höfer et al. (2016) and Sadeghi & Karimi (2017). Wind speeds often favour ridge crests (verifiable in the IOM; Fig. 7a), although flow-funnelling valleys can be suitable (Rodman & Meentemeyer, 2006). However, reduced access to these areas on the IOM is a drawback. IOM hills feature a polarisation of the highest and lowest wind speeds, potentially skewing results as granular analysis can conceal distinctions; the 250 m GWA resolution has scope for improvement. These areas feature the most extreme slope angles, and whilst generally excluded for economic reasons (Azizi et al., 2014; Schallenberg-Rodríguez & Pino, 2014; Panagiotidou et al., 2016) or due to national regulation (Satkin et al., 2014), slopes also cause undesirable turbulence and reduce wind speeds (Sarpong & Baffoe, 2015; Höfer et al., 2016). Despite this, lifting the IOM slope exclusion (> 30%) had no effect on wind speeds. The 30% exclusion is relatively high as the IOM is relatively hilly, and a stricter limitation would exclude large parts (Schallenberg-Rodríguez & Pino, 2014); Fig. 6 shows that a 15% (solar) restriction triples the criterion's excluded area. Avoiding vegetation is optimal (and environmentally beneficial) due to the increase in surface roughness reducing wind velocity (Baban & Parry, 2001; Rodman & Meentemeyer, 2006; Kushkin, 2014); however, IOM forestry plantations are often located on hills. Consequently, whilst the IOM hills feature the highest wind potential, drawbacks in terms of access, slope and vegetation weaken suitability. The equal weights sensitivity analysis reflects this, as overall suitability is reduced when these drawbacks are emphasised.

Existing IOM-based studies can validate AHP analysis. The two excluded AEA (2010) sites are due to an Area of Special Scientific Interest (ASSI (environmental area); also causing a nearby site to score 4) and the TT Course. Due to the cultural significance of the TT (a motorcycle event contributing to over a quarter of tourism income (IOM Government, 2019a; Visit IOM, 2022)), social opposition in its vicinity would be greater. Thus, buffers are used to respect the island's environment and culture, although public consultations and environmental impact assessments may enable development. The high mean suitability score indicates the analysis is valid. Under the no visual impact sensitivity analysis (theoretically exploring the raw wind potential), despite the increase in suitable area (with relaxed restrictions), general suitability declines. This could be due to the sparse population of the hilly areas, thus scoring 10 for the now-removed urban criteria, whilst the correlation between urbanity and road/electricity density somewhat undermines the scenario, as these areas remain unfavourable for safety reasons (Baban & Parry, 2001). Overall, sensitivity analysis highlights the sensitivity to criteria weights, although this is expected since the criteria were specific to the IOM (Meszaros & Rapcsak, 1996; Tegou et al., 2010).

Analysis of the Irish Sea supports the planned site to the east of the island, due to the shallow depths, high wind speeds and avoidance of environmental areas (IOM Government, 2014; Chaouachi et al., 2017; Curran, 2019). Alignment with the UK site mitigates visual impact; however, shallower waters may have greater biodiversity (Costello & Chaudhary, 2017). Also, the area would impact the Liverpool-Belfast shipping route (albeit southern ‘weather routing’ is often used alternatively (Zis et al., 2020)), producing navigational interference, increasing shipping costs, and potentially causing a ‘choke point’ between the UK wind farm to the east (MCA, 2008; Toke, 2010; Rawson & Rogers, 2015). Despite this, optimising the offshore wind location would yield significantly greater economic savings overall (Samoteskul et al., 2014).

5.2 Evaluate the suitability of the IOM for solar energy generation (objective 2)

The majority of solar PV literature focuses on countries with different solar resources to the IOM, such as Mauritius, Iran and Turkey (Doorga et al., 2019; Colak et al., 2020; Mokarram et al., 2020). These areas have annual mean irradiances (kWhm^{-2}) of 2,190, 3,400 and 1,527, respectively (*ibid.)*, raising a comparability issue, as the IOM receives 994 kWhm^{-2}; below the minimum threshold of other studies (Charabi & Gastil, 2011; Kereush & Perovych, 2017; Giamalaki & Tsoutsos, 2019). Consequently, suitability scores are relative to the IOM only, although comparisons with the UK are possible. 18.6% of a South-Central (SC) England study area (17,094 km^2, 1,000 kWhm^{-2} average irradiance) was suitable, lower than the 27.2% of suitable area on the IOM (Watson & Hudson, 2015). The SC England study applied exclusion buffers from a study of the same region focusing on wind energy (Baban &

Parry, 2001; *ibid.*). Therefore, the exclusion zone is likely overprotective of social and environmental factors, since solar has a lower environmental impact after the initial installation and generally lower social opposition (Tsoutsos et al., 2005; Hamed & Alshare, 2022); 89% of IOM respondents supported solar PV compared to 80% for onshore wind (IOM Government, 2019b). A significant proportion of the IOM hills are excluded by the slope criterion due to increased row spacing, mounting complexity, cost and shadowing (Carrión et al., 2008b; Sánchez-Lozano et al., 2013; BV, 2022).

Of the respective suitable areas, 9.3% of SC England is highly suitable, compared to 8.5% of the IOM (Watson & Hudson, 2015). The similarity in suitability is unexpected given the differences in criteria and weightings. Watson & Hudson (2015) do not weight slope aspect, simply excluding all non-SE-SW facing slopes, however, this inaccurately assumes all slopes between 135-225º receive equal sunshine; weighting aspect to prioritise south-facing slopes improves depth (Doljak & Stanojević, 2017; Doorga et al., 2019; Colak et al., 2020), although the weighting varies significantly (4.6-44%) between studies (Kereush & Perovych, 2017; *ibid.*). Similarly, Watson & Hudson (2015) do not weight the slope criteria, despite costs increasing with angle (Mokarram et al., 2020). Consequently, the north and south of the island are the most suitable for solar development (inverse to wind development) due to the higher irradiance, lower slope, appropriate aspect and proximity to road and electricity networks, accurately reflecting the theoretically optimal locations (Mierzwiak & Calka, 2017; Zoghi et al., 2017; Merrouni et al., 2018). Furthermore, after the initial (visual impact (e.g., NIMBY)) exclusion buffer, proximity to urban areas is preferable, unlike wind energy (due to the greater perceived impact of turbines), to minimise electricity transmission losses over distance (Garni & Awasthi, 2017). The airport scores 9 in suitability, and with the island's official weather station recording high sunshine here, the solar potential is high; airports are often suitable (Budd et al., 2015; Sukamaran & Sudhakar, 2017; 2018) and would help mask any socio-environmental impacts.

The planned solar site is located < 2 km from the airport and scores high in AHP analysis, validating the AHP method (PCR, 2022). However, a wildlife zone buffer partially excludes the site, indicating that the 500 m environmental exclusion zone may be too restrictive. The site – and generally most of the island – is unaffected by the no visual impact analysis, which may reflect the lower emphasis placed on social impact in the solar AHP analysis, relative to onshore wind. The increase in suitability under equal weights is potentially due to lowering the influence of the restrictive aspect and slope criteria whilst raising the importance of the relatively unrestrictive historical sites and distance to plantations. These findings contrast Watson & Hudson (2015), who find equal weights to decrease suitability (highly suitable area declines to < 0.1%), although both studies demonstrate the effectiveness of sensitivity analysis in highlighting the responsiveness to weight changes (Feick & Hall, 2004; Ishizaka & Labib, 2011). Soft PV module shading from air pollution is not likely to be an issue due to the island's good air quality, although hard shading issues may hinder potential due to the agricultural focus of the IOM (Hyder, 2009; Maghami et al., 2016). However, soiling is likely to be less problematic than in regions closer to the equator, where dust intensity is highest (Ghazi et al., 2014), and cleaning solutions to maintain efficiency exist (Mani & Pillai, 2010; You et al., 2018). The 200 m coastline buffer mitigates soiling via sea salt precipitates whilst also reducing social impact (Georgiou & Skarlatos, 2016; Giamalaki & Tsoutsos, 2019; Oehler et al., 2020).

Despite a larger inclusion area, comparing AHP value scores suggests the IOM is more suited to wind energy. Whilst this may be true given the climate, AHP analysis would not account for this due to different criteria scaling and buffers. Standardising AHP weights may also inaccurately reflect criteria. For example, IOM solar irradiance shows little variance (± 27 $kWhm^{-2}$), however, assigning a low-value score heavily deters suitability ranking (although sensitivity analysis helps (Nekhay et al., 2009)). For this reason, Uyan (2013) do not consider irradiance (± 25 kWm^{-2}) as a criterion; an alternative approach that could improve the study. Overall, this novel study builds on existing knowledge to highlight that both energy sources in the IOM generally reflect the viability (and drawbacks) established in the UK and on a global scale.

5.3 Examine the wind and solar energy generation potential of the IOM (objective 3)

The generation potential can be crudely estimated based on rated capacity, suitable area, placement properties and load factors. However, these factors are basic (for example, optimal turbine and array placement are generalised, high-level theory, not accounting for local context and topography (Patel, 2006; Curran, 2019)) and only offer an insight into the potential. With these limitations and uncertainties in mind, upper-bound estimates suggest onshore wind (1.3 GW), offshore wind (1.2 GW) and solar PV (17.4 GW) could all significantly exceed peak IOM demand (maximum 84.8 MW) under optimal conditions, reflecting the high potential identified globally (Ellabban et al., 2014; Twidell, 2021). The onshore wind and solar PV values assume the highly unfeasible installation of the respective technology at all suitable sites, therefore values for higher potential land (> 8; 396 MW and 1.5 GW, respectively) are more realistic. Applying load factors increases the realism, despite being estimated averages which vary between studies (Curran, 2019; IOM Government, 2021). All sources remain above the generation requirement with load factors, although solar would not meet demands when applying more conservative estimations, such as 4.5, 7 or 10 acres per MW (Lopez et al., 2012; Stoms et al., 2013; Macknick et al., 2013); the 2.5 acres per MW estimate was from an IOM-based study (Curran, 2019).

An approach that integrates renewable technologies provides optimal generation potential, offering greater reliability and stability that alleviates intermittency issues and reduces storage requirements (Hart et al., 2010; Zhou et al., 2010; Badwawi et al., 2015). Solar and wind can exhibit complementary generation on both daily and annual timescales, exemplified on the IOM with higher winter wind speeds and higher summer sunshine, although fog (reducing efficiency by up to 38%) is most prominent during the summer (Liu et al., 2018; Slusarewicz & Cohan, 2018). Additionally, whilst correlation does not imply causation, the energy demand-wind speed relationship is favourable for optimising performance (Fig. 16a), unlike the demand-sunshine (Fig. 16b) relationship (Al-Yahyai et al., 2012; Aisyah & Simaremare, 2021). Wind diurnal variation also decreases with turbine height (Bansal et al., 2002). Given the island's climate, temperature-related solar PV losses (occurring at 25ºC) are unlikely (Huld & Amillo, 2015), even with the observed and projected climate warming; especially as modelled climate change impacts on solar PV are minor and IOM data show an increase in sunshine (Gernaat et al., 2021). Whilst prolonged calm periods may be concerning, climate change impacts on wind energy are uncertain (*ibid.*). Turbines and solar panels have been criticised for unsustainable manufacturing (such as metal and mineral mining) and decommissioning processes (Anderson et al., 2014; Church & Crawford, 2020), although improvements are ongoing (Jensen, 2019). Regardless, with expected consumption increases (131 MW by 2050 (IOM Government, 2021)), renewable energy will be required in some capacity to balance demand, and this study highlights the significant potential for both wind and solar energy on the IOM.

5.4 Study limitations

This study contributes towards the increasing breadth of research validating the GIS-AHP method; however, the study is limited by a number of shortcomings. Despite the benefit of quantifying planning criteria, variables are subjective, and the assignment of importance weights is inconsistent within the literature. Baban and Parry (2001), Bennui et al. (2007), Ramírez-Rosado et al. (2008) and Tegou et al. (2010) all utilise the GIS-AHP method, however, none explain weight assignments (Höfer et al. 2016). Georgiou et al., (2012), Watson & Hudson (2015) and Höfer et al. (2016) use expert interviews to establish criteria importance but produce different rankings, highlighting the subjectivity. Therefore, inconsistency in AHP evaluation weakens comparability due to a reduction in controlled variables, although AHP is designed to be specific to a study region whilst planning is an inherently subjective issue. This study has involved no expert consultation and thus has adapted criteria from studies that best conform to the IOM, such as the wind study that emphasises social and environmental concerns (Höfer et al., 2016). Other studies heavily prioritise wind resource as the dominant criterion (Al-Yahyai et al., 2012; Sarpong & Baffoe, 2015; Villacreses et al., 2017). Furthermore, exclusion zones have been identified from literature due to a lack of local energy planning legislation, and inconsistency (due to legislative differences, subjectivity and local context) between studies results in the estimation of appropriate exclusions (Şener et al., 2010; Langnan-Newton, 2023).

Roads of uniform size have been assumed, despite the fact that IOM roads are often small, winding and surrounded by trees that inhibit accessibility. Turbine innovation is a solution; modular blades enable on-site construction, thus improving logistics (GE, 2023). Shadow flicker, glare/reflectivity, avian flight routes, geology, underground pipelines, telecommunications lines, land developments, private landownership, land value, land cover, horse routes and archaeology have not been thoroughly assessed as a lack of data and time constraints limit study depth, although exclusion buffers will cover some of these. However, the debate over buffer usage suggests it provides only a high-level indication of suitability; detailed, site-specific surveys would improve resolution. The aforementioned model uncertainties also caveat findings, whilst flood maps are indicative and lack spatial resolution (IOM Flood Hub, 2023). Despite these limitations, ample discussion of each research objective has largely been achieved, enabled by a generally valid and comparable set of results for the IOM.

6. Conclusion

This study highlights that the IOM has a high potential for wind and solar energy developments; a potential that is currently unexploited. The findings presented are highly relevant for informing island policies and energy development plans amid climate change and energy security concerns. Onshore wind development is suitable in 22.9% of the IOM, with 8.5% being highly suitable; in particular, the central and southwestern hills, given their higher wind speeds and sparse populations. Slightly more (27.2%) of the IOM is suitable for large-scale solar PV development, however, the highly suitable area occupies a quarter of the equivalent wind area, meaning the wind energy potential is higher. The north and south of the IOM are more favourable for solar PV given the flatter land and increased connectivity, contrasting wind energy. Analysis also suggests the planned Irish Sea offshore wind farm is located optimally, primarily due to the shallower depth. Finally, onshore wind, offshore wind and solar PV generation could all individually exceed island demand, based on crude estimates derived from the spatial analysis. This builds on knowledge of the potential of renewable energy and emphasises the physical potential of the IOM.

Overall, these findings generally reflect the theoretically optimal sites for renewable installation, and thus largely validate the reliability and accuracy of the GIS-AHP method; the first study of its kind for the IOM. Suitability analysis placed a greater emphasis on social acceptance, differentiating it from conventional site selection studies that focus on the raw renewable energy potential, thus offering a more socially realistic and human-centric set of results. Consequently, this study also contributes to understanding of the site selection process and how buffers can be used effectively in pilot studies. The study would be enhanced by data improvements such as in urban resolution (e.g., property-level mapping), avian flight routes, and detailed land ownership information. Similarly, modelling uncertainties caveat findings and appropriate ground truthing would improve confidence in data reliability. However, findings are primarily limited by a lack of expert opinion to determine criteria weights; future research that involves IOM-specific expert consultation would improve the study. Other opportunities for future research include further public consultations, environmental and visual impact assessments, financial analyses, energy storage technology investigations, and repeating the study with experimental alterations, such as using a reference wind turbine of average (i.e., smaller) capacity.

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Appendix

Figure 1. (a) Sources of energy in the UK in 2022 based on the actual generation provided by each (in GW) (Morley, 2023). **(b)** Current sources of IOM energy generation based on their potential (in MW). Pulrose CCGT denotes the combined cycle gas turbine station, and EfW denotes the Energy from Waste plant (IOM Government, 2021a).

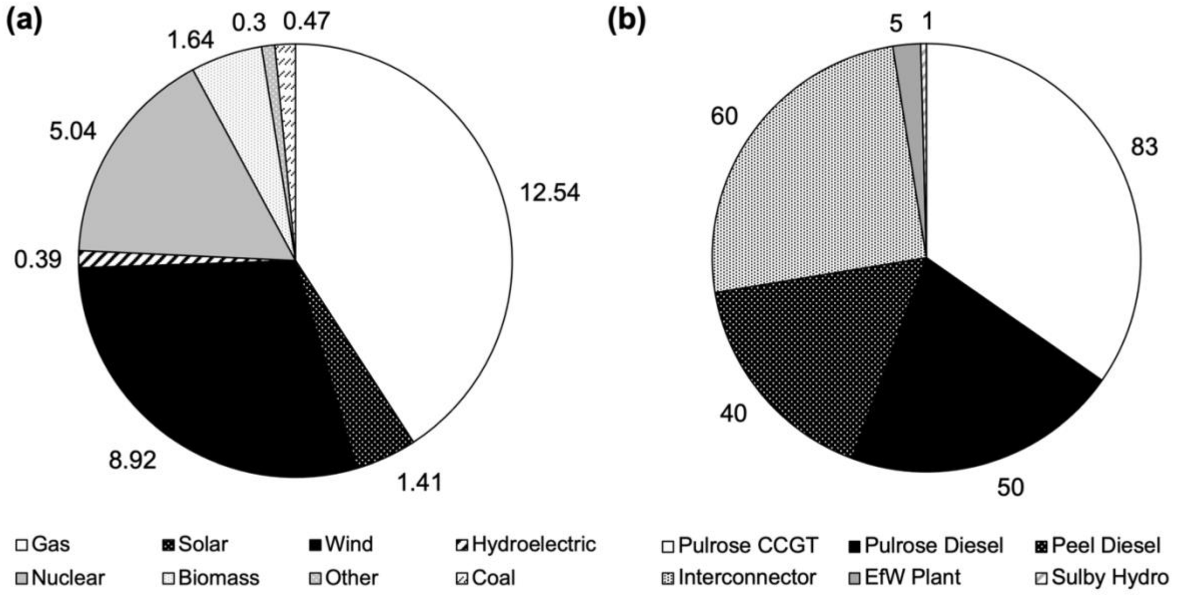
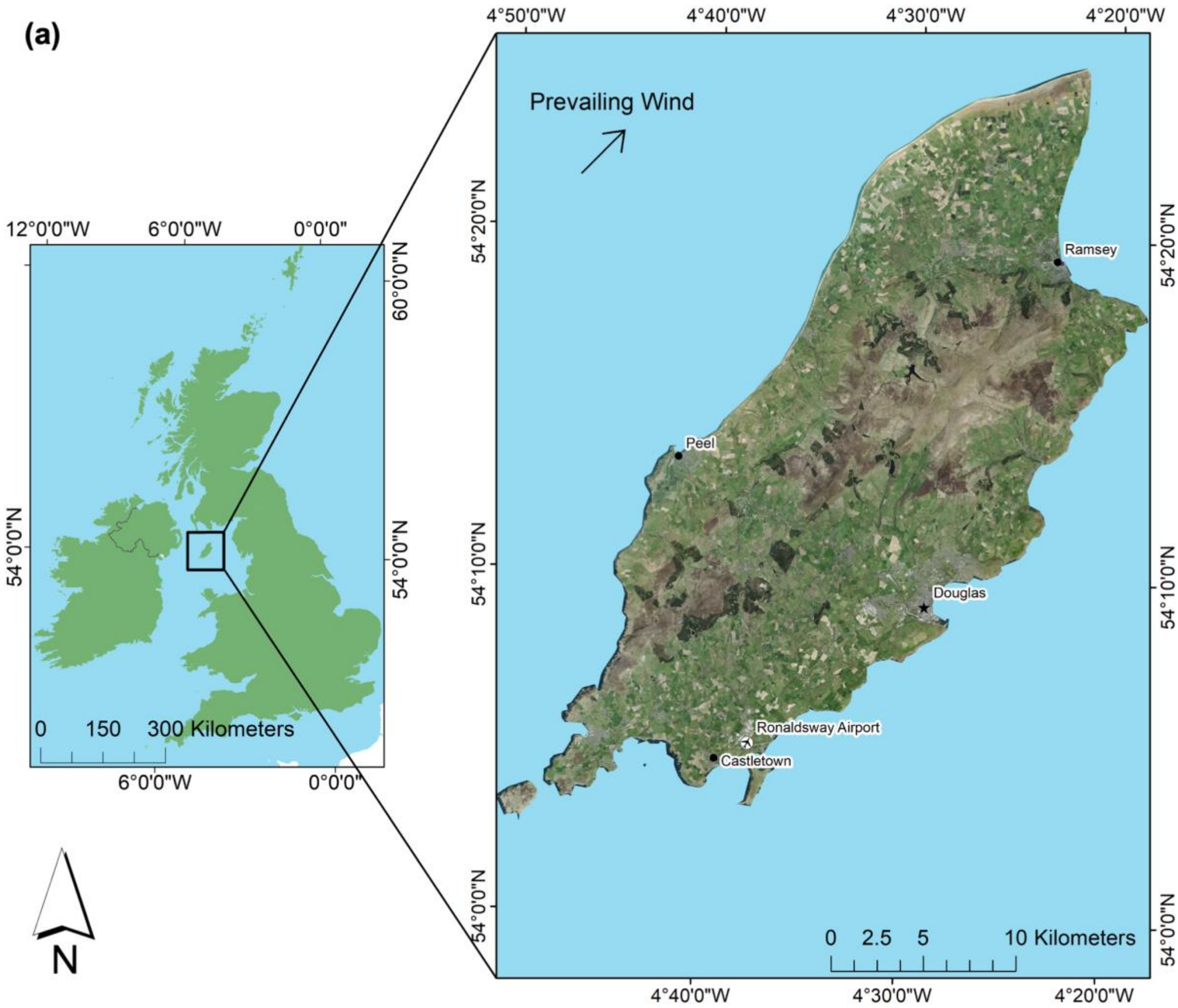
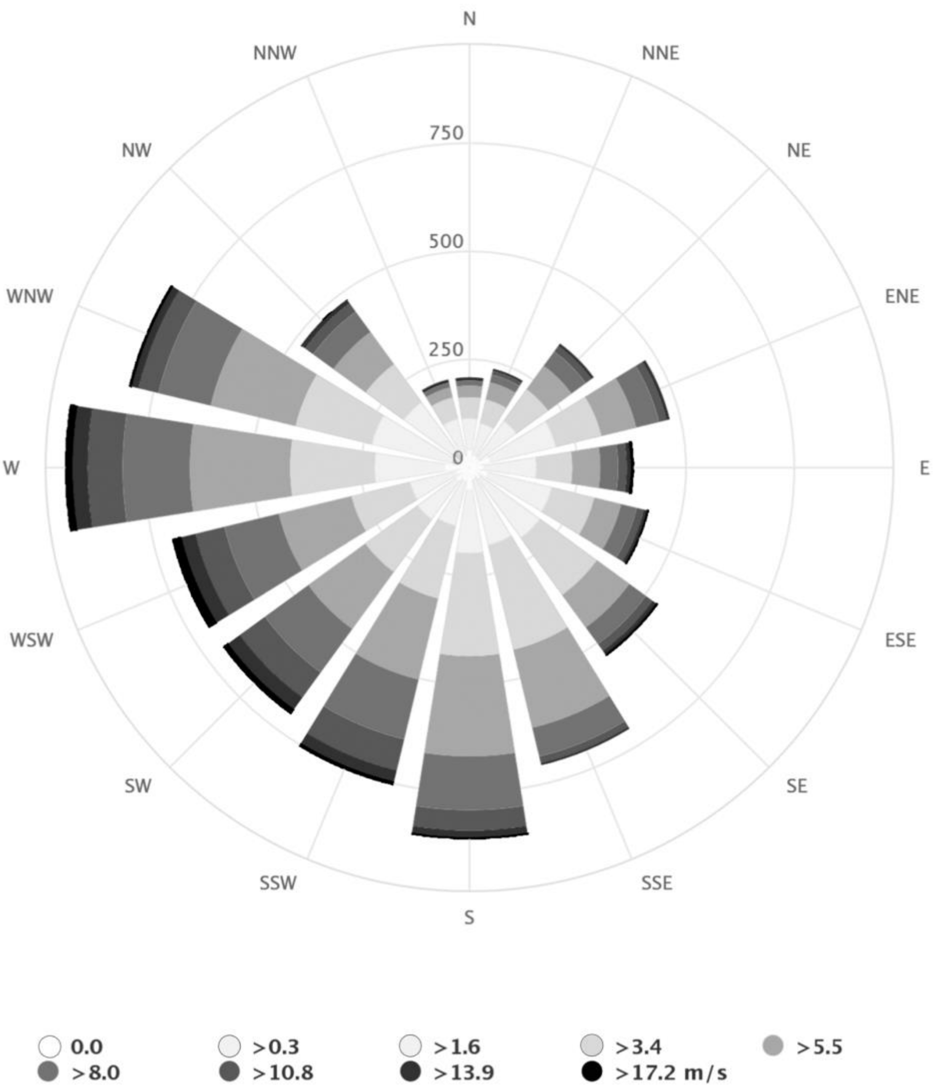


Figure 2. (a) Study site of the IOM, located in the Irish Sea, between England and Northern Ireland. Major settlements, the airport and the prevailing wind direction (SW) are highlighted on a 2018 satellite image (IOM Government, *pers. comm.*; GADM, 2023). **(b)** IOM annual wind rose calculated from mean wind speeds (ms^{-1}), based on the number of hours per year the wind blows from the specified direction (adapted from MeteoBlue, 2023).



(b)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0.0
>0.3
>1.6
>3.4
>5.5
>8.0
>10.8
>13.9
>17.2 m/s

Table 1. Data sources and formats. Italic text denotes a process undertaken within ArcMap.

Source	Format	Content
Global Wind Atlas (GWA, 2021)	Raster (GeoTIFF/TIF)	Mean wind speed (at 10 m, 50 m and 100 m heights) Irish Sea bathymetry
Global Solar Atlas (SolarGIS, 2022)	Raster (GeoTIFF/TIF)	Solar irradiance: global horizontal (GHI), direct normal irradiance (DNI), optimum solar panel tilt angles, global irradiance at the optimum tilt angle, air temperature (at 2 m), and solar PV potential (PVOUT; a modelled simulation based on the other solar PV inputs)
Database of Global Administrative Areas (GADM, 2023)	Feature class (shapefile)	Country (IOM, UK and ROI) area extents
Marine Regions (Marine Regions, 2015)	Feature class (shapefile)	Ocean (Irish Sea and North Atlantic Ocean) area extents
European Marine Observation and Data Network (EMOD, 2022)	Feature class (shapefile)	Active offshore wind farms Subsea pipelines/cables Shipping vessel densities Marine environmental protection areas

Morecambe (2022)	*Georeferenced into feature class (shapefile) from image*	Morecambe planned offshore wind farm
EnBW-BP (2022)	*Georeferenced into feature class (shapefile) from image*	Mona and Morgan planned offshore wind farms
IOM Government, Department of Infrastructure, Highway Services (*pers. comm.)*	Feature class (shapefile)	Road networks
		Water body extents
	Raster (MrSID)	Satellite imagery (2018)
	Raster (ASCII)	5 m Digital Terrain Model
		2 m Digital Surface Model
IOM Government, Department of Infrastructure, Flood Management Division (*pers. comm.)*	Feature class (shapefile)	Flood risk maps (high risk flood zones)
Manx Utilities (*pers. comm.)*	Feature class (shapefile)	Government-owned land
	Feature class (file geodatabase – *converted into shapefile)*	Electricity network extent
	Microsoft Excel data	Electricity demand data
IOM Government (2023)	*Georeferenced into feature class (shapefile) from image*	Public Right of Way (PROW; footpath) routes
IOM Government, Department of Environment, Food and Agriculture (DEFA, 2023)	*Georeferenced into feature class (shapefile) from image*	Environmental protection areas
Manx National Heritage (2023)	*Georeferenced into feature class (shapefile) from image*	Historical sites

Table 2. ArcMap tools and functions used (ESRI, 2023).

Tool *(or function)*	Description
Georeferencing	Assigns spatial reference information to maps or satellite imagery that lack this information
Create signatures	Generates signature data of classes based on input sample data and its raster bands (colours)
Maximum likelihood classification	A multivariate analysis algorithm that assigns cells to classes defined in the *create signatures* file based on a probability of its raster bands (colours)
Slope	Calculates the slope (gradient/steepness) of each raster cell
Raster calculator	Constructs and executes a Python syntax-derived expression using Map Algebra (algebraic spatial analysis)
Buffer	Generates polygons around features to a specified distance
Raster to polygon	Converts an integer raster input dataset into polygon (feature class) features
Cell statistics	Calculates statistics (e.g., majority, mean, standard deviation) of cells from multiple raster datasets
Aspect	Calculates the compass direction a slope is facing (0-360º)
Focal statistics	Calculates a statistic (e.g., mean) of the neighbourhood cells (of a specified distance) that surrounds each input cell
Explode multipart feature	Separates joined features with multiple parts into individual features
Calculate geometry	Generates attribute information (e.g., area) for each feature
Euclidean distance	Calculates the distance of each cell from a source feature
Reclassify	Reclassifies raster values based on user input
Weighted overlay	Uses a standardised measurement scale to overlay multiple raster inputs, accounting for importance weights
Merge	Combines multiple datasets into a single dataset
Erase	Removes a specified extent from input features
Clip	Extracts features that overlay the specified clip extent

Generate tessellation	Generates a tessellated grid of regular polygons that cover a specified extent
Feature vertices to points	Creates points at specified feature vertices (e.g., corners of a polygon)
Generate points along lines	Creates points at specified intervals along a feature's length
Mosaic to new raster	Combines multiple raster inputs into a single raster dataset
Extract by mask	Extracts raster cells that overlay the specified mask extent (similar to the clip tool)
Zonal statistics	Calculates statistics (e.g., mean) of an input dataset

Figure 3. The methodological framework for onshore wind and solar PV siting, adapted from Tegou et al. (2010) and Höfer et al. (2016).

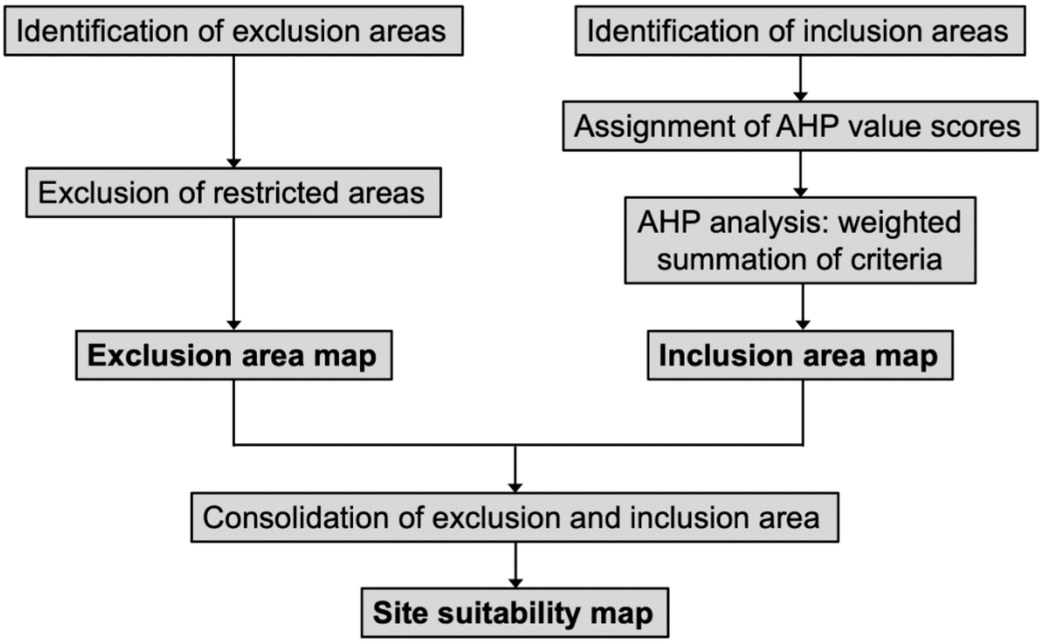


Table 3. Onshore wind AHP criteria weightings (%) and exclusion zones, adapted from Höfer et al. (2016). Exclusion zones not requiring scaled/weighted distances (not contributing towards the AHP process) are also shown, denoted by a dash (-).

Criteria	Importance weighting (%)	Exclusion buffer/criteria (m)
Wind energy potential	21	< 5 ms^{-1} at 50 m elevation
Protected environment	20	500
Urban areas	18	500
Electricity grid	7	220 overhead lines, 0 underground cables
Road network	7	220
Historical sites	7	500
Landowner	6	N/A
Land cover type	6	N/A
Slope	4	> 30%
Flood zone	4	N/A
Airport	-	3000
Railway	-	220
PROW	-	220, 600 on popular horse routes
TT Course	-	500
Coastline	-	200

Table 4. Solar PV AHP criteria weightings (%) and exclusion zones, primarily adapted from Kereush and Perovych (2017), Mierzwiak and Calka (2017) and Colak et al. (2020). Exclusion zones not requiring scaled/weighted distances (not contributing towards the AHP process) are also shown, denoted by a dash (-).

Criteria	Importance weighting (%)	Exclusion buffer/criteria (m)
Solar potential (PVOUT)	25	N/A
Aspect	20	N/NE/NW
Slope	14	> 15%
Electricity grid	14	10 overhead lines, 0 underground cables
Road network	7	10
Urban areas	5	500
Landowner	5	N/A
Land cover type	5	N/A
Historical sites	5	500
Protected environment	-	500
Railway	-	10
PROW	-	10
Water body & flood risk	-	Water body & flood risk zone
Coastline	-	200

Table 5. Onshore wind site selection criteria value scores. The value scores (VS) are listed for wind speed (WS), protected environment (PE), urban areas (UA), electricity grid (EG), road network (RN), historical site (HS), landowner (LO), plantations and heathland (PH), slope (S%) and flood risk (FR). Units are metres except for value score (dimensionless value), wind speed (ms^{-1}) and slope (%). Non-AHP exclusion zones (Table 3) are excluded. *The electricity grid 220 m safety setback distance only applies to overhead high voltage lines; underground cables are not excluded.

VS	WS	PE	UA	EG	RN	HS	LO	PH	S%	FR
0	< 5	< 500	< 500	< 220*	< 220	< 500	-	-	> 30	-
1	5-5.75	500-600	500-650	> 1650	> 1650	500-600	Other	-	27-30	High FR
2	5.75-6.5	600-700	650-800	1500-1650	1500-1650	600-700	-	0-150	24-27	-
3	6.5-7.25	700-800	800-950	1350-1500	1350-1500	700-800	-	-	21-24	-
4	7.25-8	800-900	950-1100	1200-1350	1200-1350	800-900	-	150-300	18-21	-
5	8-8.75	900-1000	1100-1250	1050-1200	1050-1200	900-1000	-	-	15-18	-
6	8.75-9.5	1000-1100	1250-1400	900-1050	900-1050	1000-1100	-	300-450	12-15	-
7	9.5-10.25	1100-1200	1400-1550	750-900	750-900	1100-1200	-	-	9-12	-
8	10.25-11	1200-1300	1550-1700	600-750	600-750	1200-1300	-	450-600	6-9	-
9	11-11.75	1300-1400	1700-1850	450-600	450-600	1300-1400	-	-	3-6	-
10	> 11.75	> 1400	> 1850	220*-450	220-450	> 1400	IOM Gov	> 600	0-3	Other

Table 6. Solar PV site selection criteria value scores. The value scores (VS) are listed for solar potential (PVOUT), aspect (A), slope (S%), electricity grid (EG), road network (RN), urban areas (UA), landowner (LO), plantations and heathland (PH) and historical sites (HS). Units are metres except for value score (dimensionless value), PVOUT (kWh/kWp), aspect (compass direction) and slope (%). Non-AHP exclusion zones (Table 4) are excluded. *The electricity grid 10 m safety buffer only applies to overhead high voltage lines; underground cables are not excluded.

VS	PVOUT	A	S%	EG	RN	UA	LO	PH	HS
0	-	N, NW, NE	>15	< 10*	< 10	< 500	-	-	< 500
1	2.48-2.52	E, W	12-15	> 2250	> 2250	> 5000	Other	-	500-600
2	2.52-2.56	-	10-12	2000-2250	2000-2250	4500-5000	-	0 - 150	600-700
3	2.56-2.6	-	8-10	1750-2000	1750-2000	4000-4500	-	-	700-800
4	2.6-2.64	-	6-8	1500-1750	1500-1750	3500-4000	-	150-300	800-900
5	2.64-2.68	-	5-6	1250-1500	1250-1500	3000-3500	-	-	900-1000
6	2.68-2.72	SE, SW	4-5	1000-1250	1000-1250	2500-3000	-	300-450	1000-1100
7	2.72-2.76	-	3-4	750-1000	750-1000	2000-2500	-	-	1100-1200
8	2.76-2.8	-	2-3	500-750	500-750	1500-2000	-	450-600	1200-1300
9	2.8-2.84	-	1-2	250-500	250-600	1000-1500	-	-	1300-1400
10	> 2.84	S, flat	0-1	0-250	10-250	500-1000	IOM Gov	> 600	> 1400

Figure 4. (a) The mathematical formulation to calculate the site suitability value of cell *x*, where *n* is the total number of criteria, w_y is the importance weight of criterion *y*, and v_{xy} is the score of cell *x* with criterion *y* (adapted from Yoon & Hwang (1995) and Tegou et al. (2010)). The ArcMap *raster calculator* AHP expressions for **(b)** onshore wind and **(c)** solar PV, to calculate respective site suitability.

(a)

Site suitability for cell $x = \sum_{y=1}^{n} w_y v_{xy}$

(b)

Onshore wind site suitability = (wind energy potential × 0.21) + (protected environment × 0.20) + (urban areas × 0.18) + (electricity grid × 0.07) + (road network × 0.07) + (historical sites × 0.06) + (landowner × 0.06) + (land cover type × 0.06) + (slope × 0.04) + (flood zone × 0.04)

(c)

Solar PV site suitability = (solar potential × 0.25) + (aspect × 0.20) + (slope × 0.14) + (electricity grid × 0.14) + (road network × 0.07) + (urban areas × 0.05) + (landowner × 0.05) + (land cover type × 0.05) + (historical sites × 0.05)

Figure 5. IOM onshore wind exclusion zones, illustrating the criteria and their required separation distance. Map produced using the *buffer*, *erase* and *raster calculator* ArcMap tools.

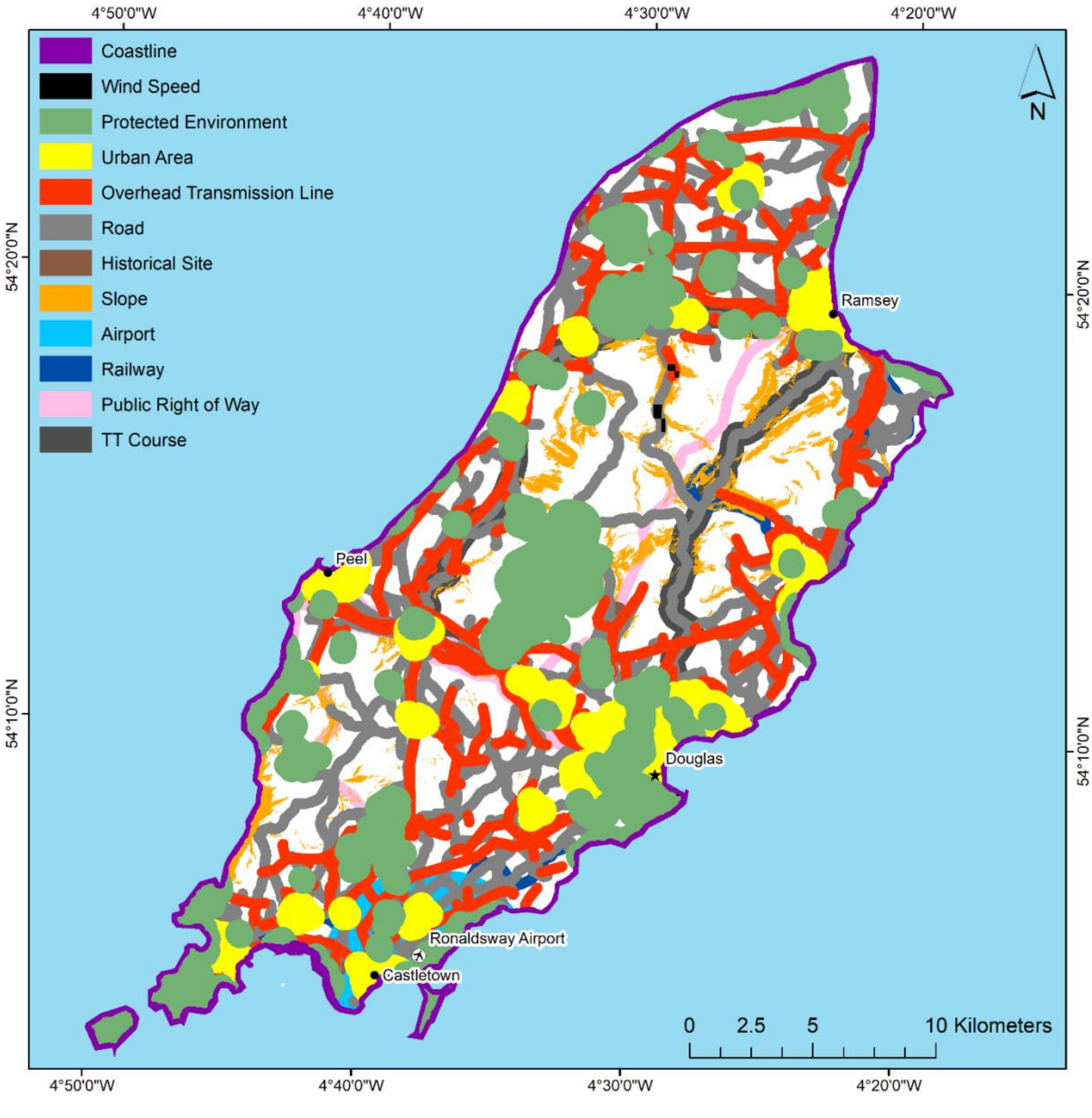


Figure 6. Percentage of excluded area relative to total area, for each onshore wind and solar PV criterion.

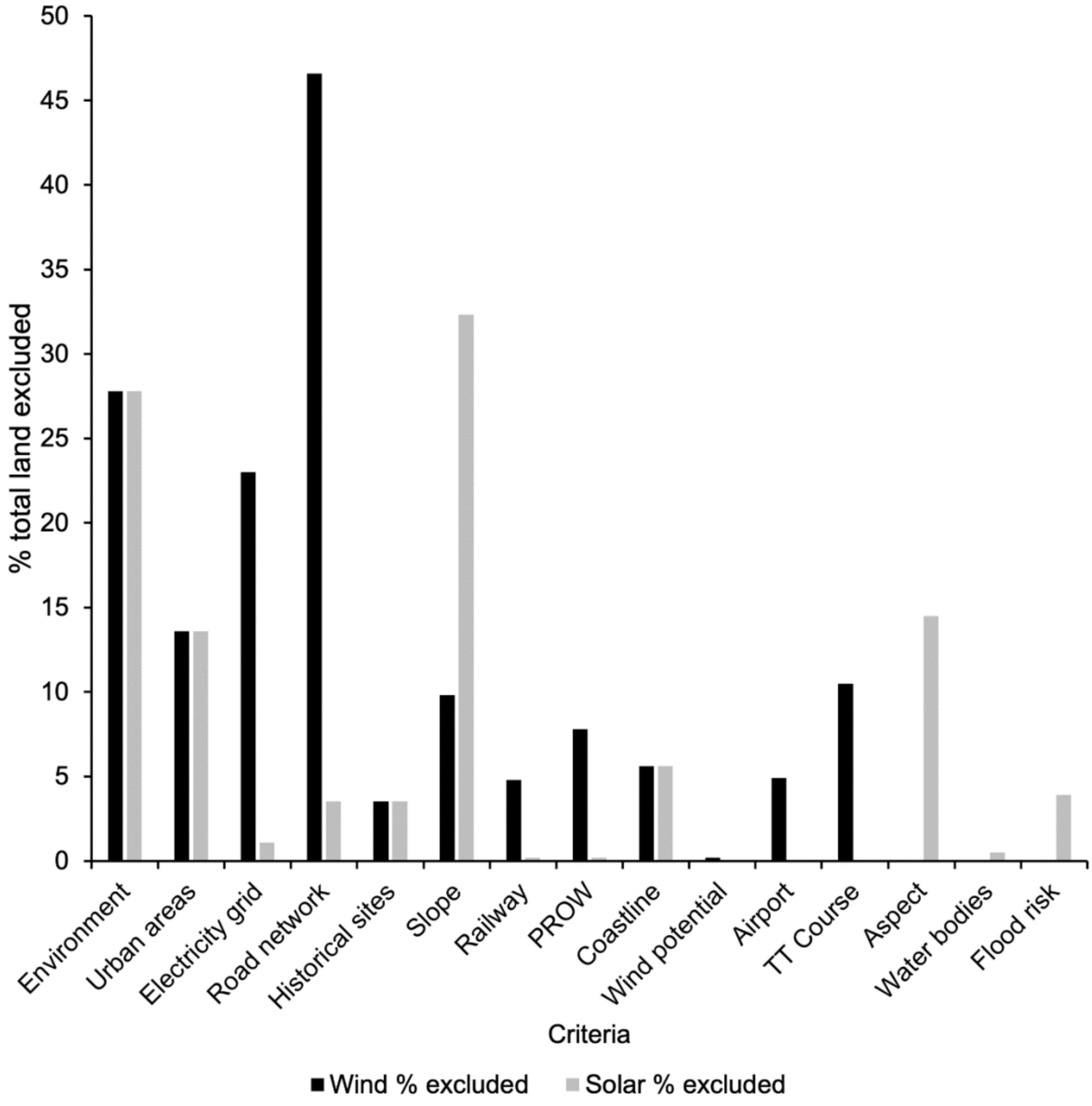


Figure 7. IOM onshore wind site suitability value score according to the criteria **(a)** wind energy potential, **(b)** distance to protected environments, **(c)** distance to urban areas, **(d)** distance to electricity grid, **(e)** distance to roads, **(f)** distance to historical sites, **(g)** distance to plantations and heathland, **(h)** slope angle and **(i)** landowner and flood risk. Maps produced using the *reclassify* and *Euclidean distance* tools.

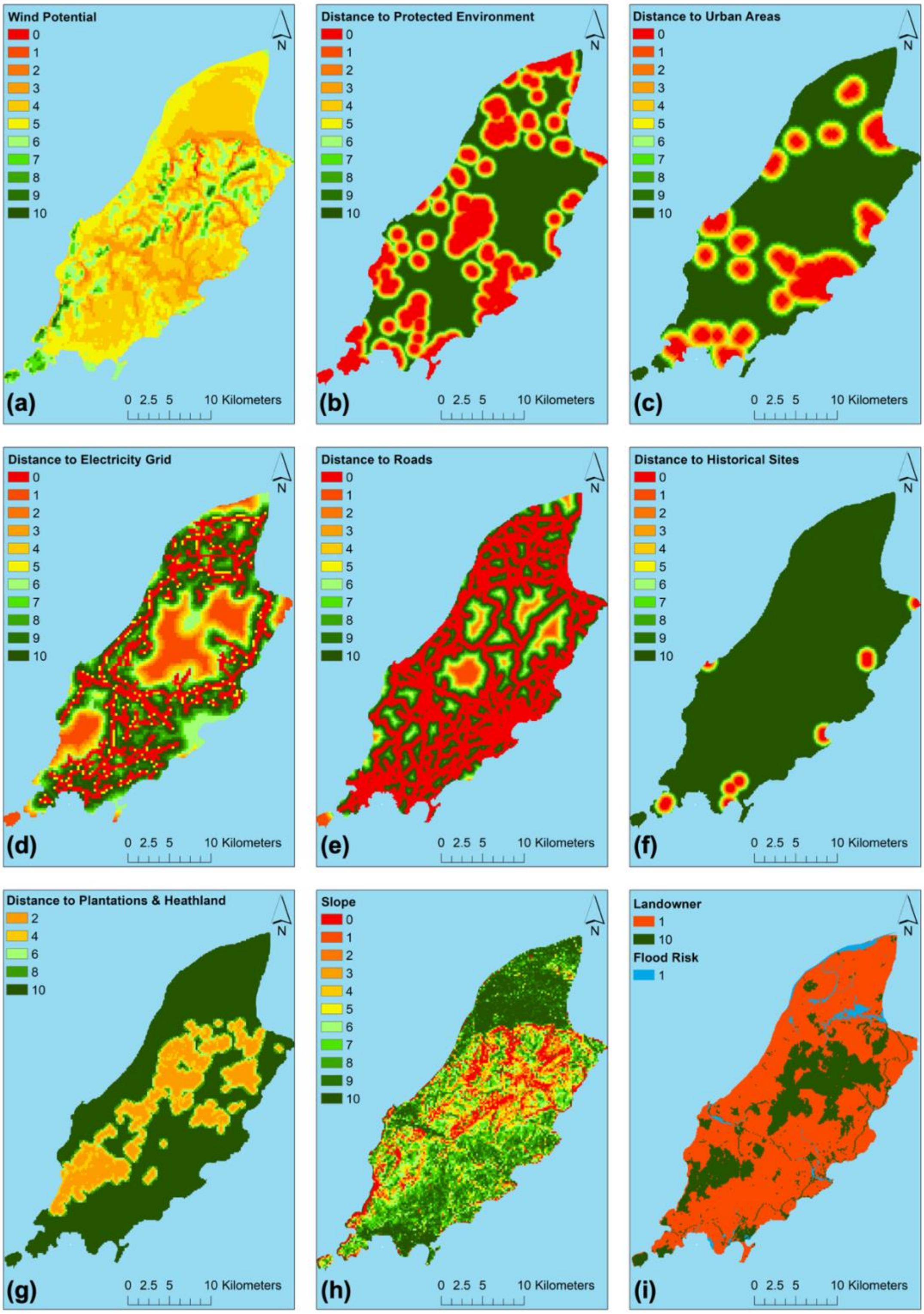


Table 7. IOM suitable area for onshore wind development, according to AHP analysis results and two types of sensitivity analysis.

Value Score	AHP			Equal Weights			No Visual Impact		
	Area (km^2)	% of total area	% of suit-able area	Area (km^2)	% of total area	% of suit-able area	Area (km^2)	% of total area	% of suit-able area
1	0.0	-	-	0.0	-	-	0.0	-	-
2	0.0	-	-	0.0	-	-	< 0.1	< 0.1	< 0.1
3	< 0.1	< 0.1	< 0.1	0.0	-	-	0.2	< 0.1	0.2
4	0.4	0.1	0.3	0.1	< 0.1	< 0.1	3.3	0.6	2.4
5	5.3	0.9	4.0	2.8	0.5	2.3	14.7	2.6	10.8
6	20.5	3.6	15.7	27.5	4.8	21.9	44.6	7.8	32.7
7	56.3	9.8	43.1	58.4	10.2	46.5	49.8	8.7	36.5
8	46.9	8.2	35.9	35.6	6.2	28.3	23.0	4.0	16.9
9	1.2	0.2	0.9	1.3	0.2	1.0	0.7	0.1	0.6
10	< 0.1	< 0.1	< 0.1	0.0	-	-	< 0.1	< 0.1	< 0.1
Total	130.7	22.9	-	130.7	22.9	-	136.4	23.8	-
Total Area 572 km^2									

Figure 8. IOM onshore wind inclusion zone site suitability analysis based on site selection criteria and AHP, overlaid on a 2 m LiDAR digital surface model of the IOM. Site suitability is based on the value score of each cell. Exclusion zones have been removed, meaning only inclusion zones are depicted; note that no inclusion areas scored ≤ 2. High potential wind sites identified from the AEA (2010) and BV (2022) studies are shown. Map produced using the *raster calculator* (for AHP analysis), *convert to feature class* and *erase* ArcMap tools.

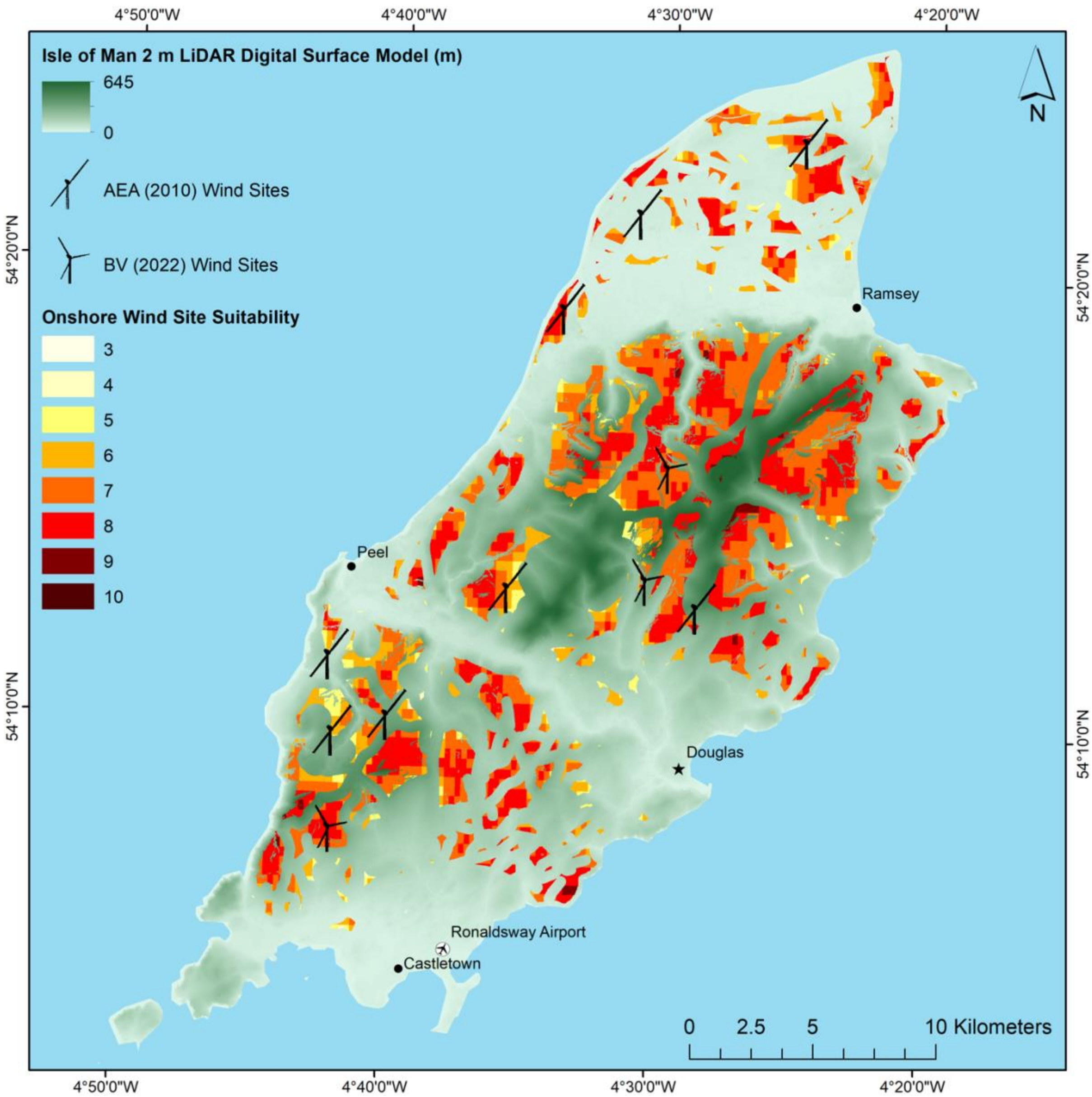


Figure 9. IOM planned offshore wind site illustrated between the 6- and 12-nautical mile territorial limits, overlaid on a bathymetry base map. Greater than 0.8 average hours/km^2 vessel density (2021) is defined as a popular shipping route (EMOD, 2022). Wind speed at 50 m is between 9-10 ms^{-1} unless marked as < 9 ms^{-1}. Map produced using *raster calculator*, *extract by mask* and *reclassify* ArcMap tools, in combination with digitising features from the editor and georeferencing toolbars.

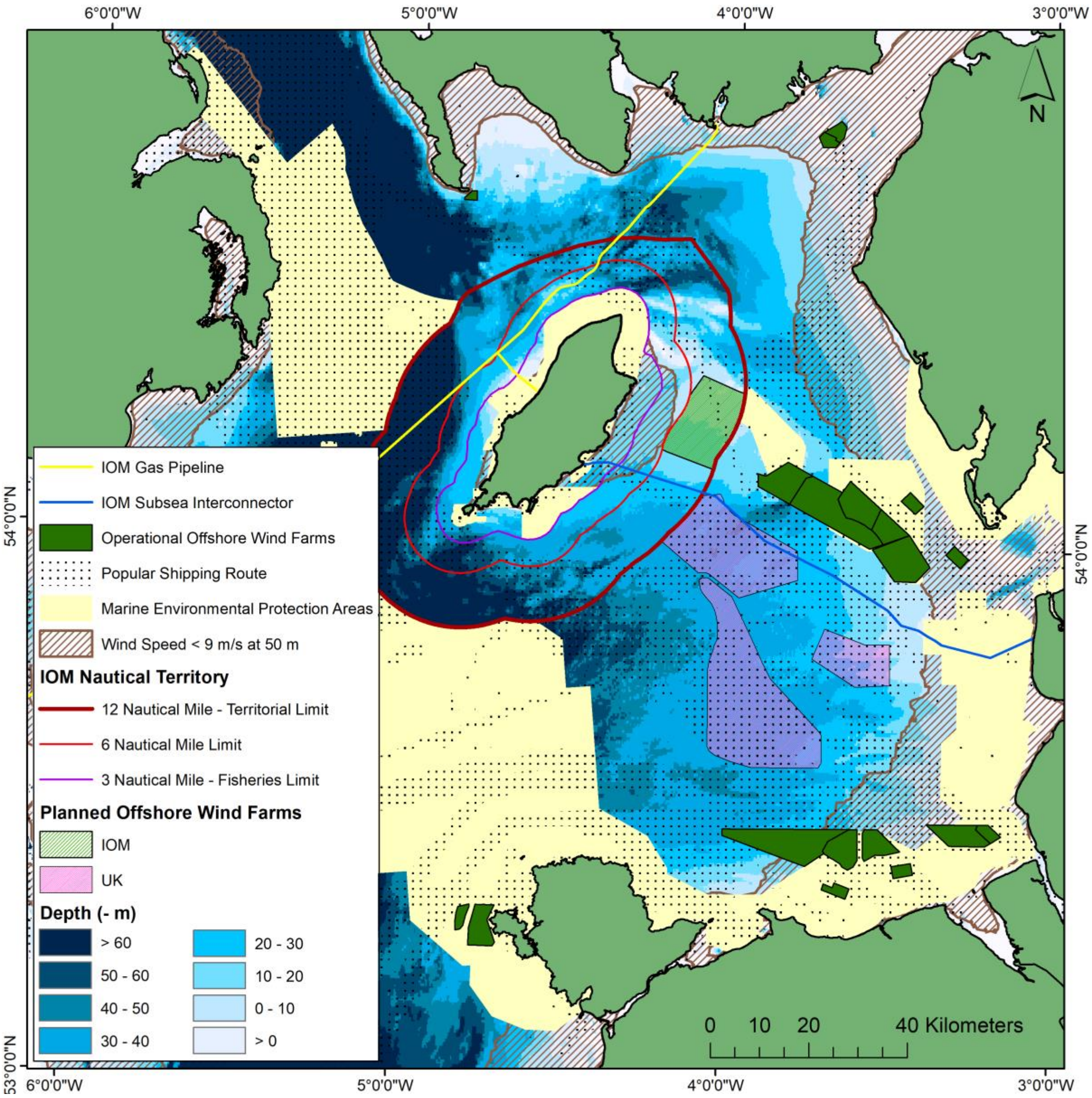


Figure 10. IOM solar PV exclusion zones, illustrating the criteria and their required separation distance. Map produced using the *buffer*, *erase* and *raster calculator* ArcMap tools.

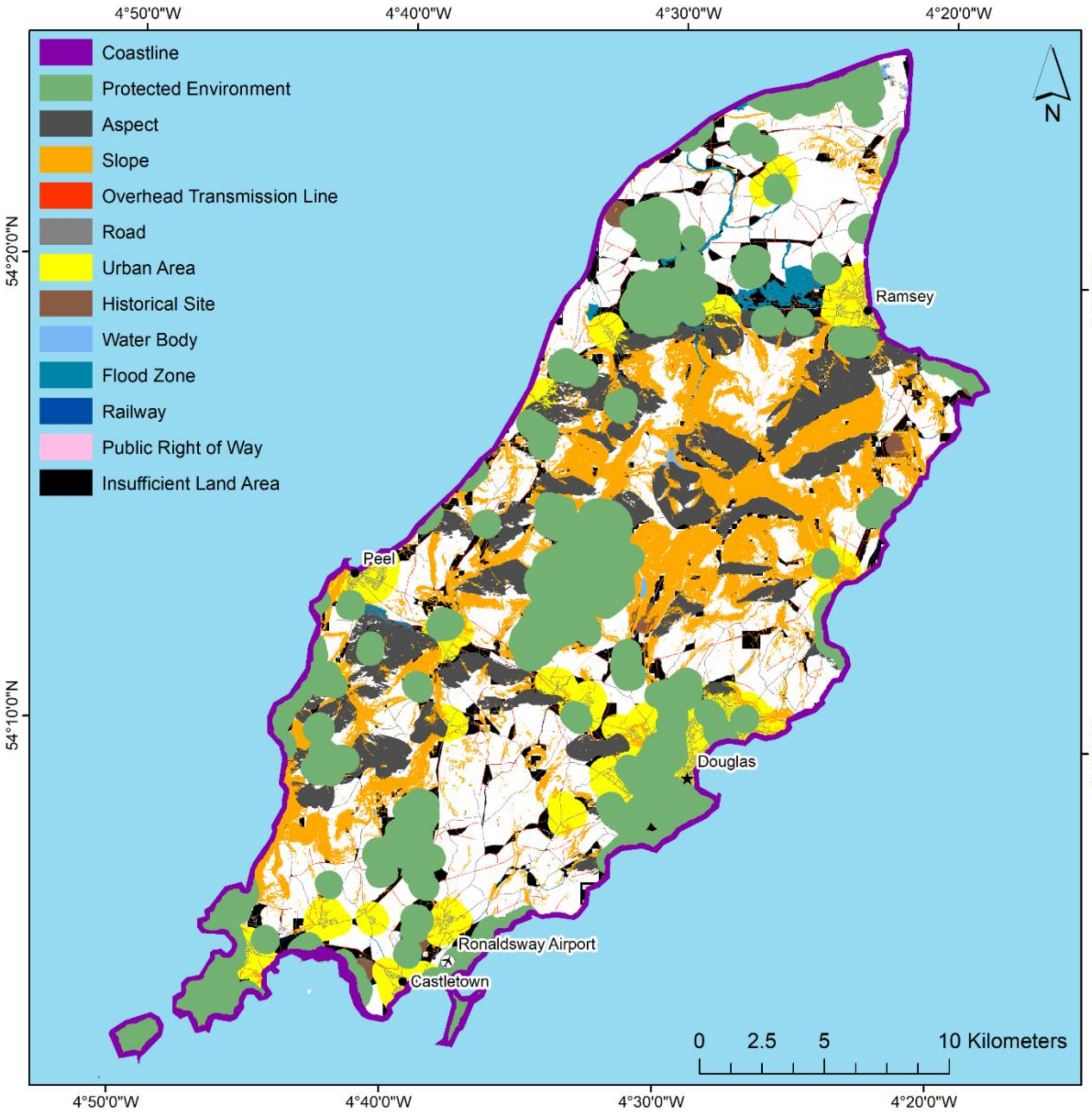


Figure 11. IOM solar PV site suitability value score according to the criteria **(a)** solar irradiation potential, **(b)** aspect, **(c)** slope angle, **(d)** distance to electricity grid, **(e)** distance to roads, **(f)** distance to urban areas, **(g)** landowner, **(h)** distance to plantations and heathland and **(i)** distance to historical sites. Maps produced using the *reclassify* and *Euclidean distance* tools.

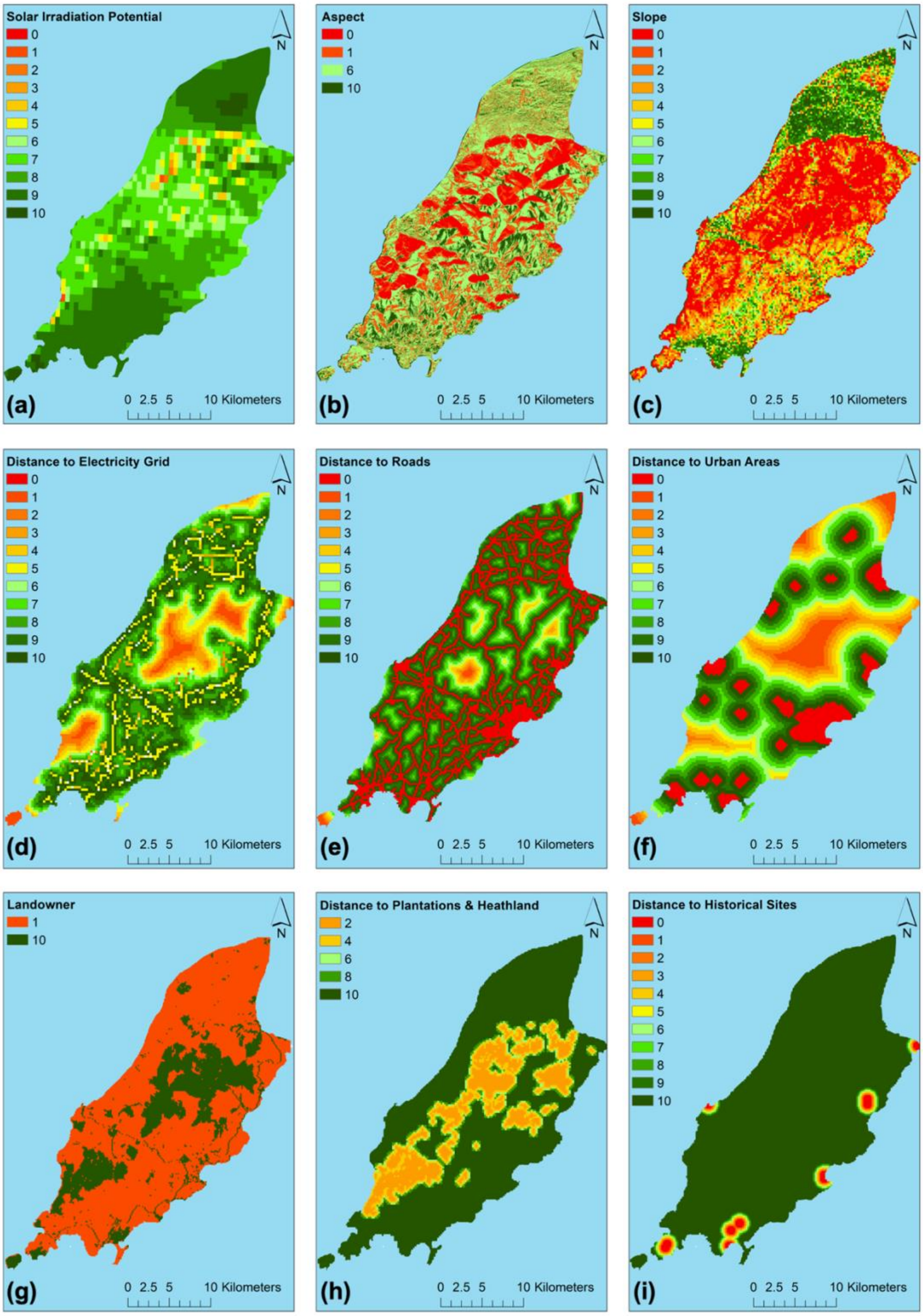


Figure 12. IOM solar PV on zone site suitability analysis based on site selection criteria and AHP, overlaid on a 2 m LiDAR digital surface model of the IOM. Site suitability is based on the value score of each cell. Exclusion zones have been removed, meaning only inclusion zones are depicted; note that no inclusion areas scored ≤ 2 or ≥ 9. A high potential site in the south of the IOM identified in the PCR (2022) study is also shown. Map produced using the *raster calculator* (for AHP analysis), *convert to feature class* and *erase* ArcMap tools.

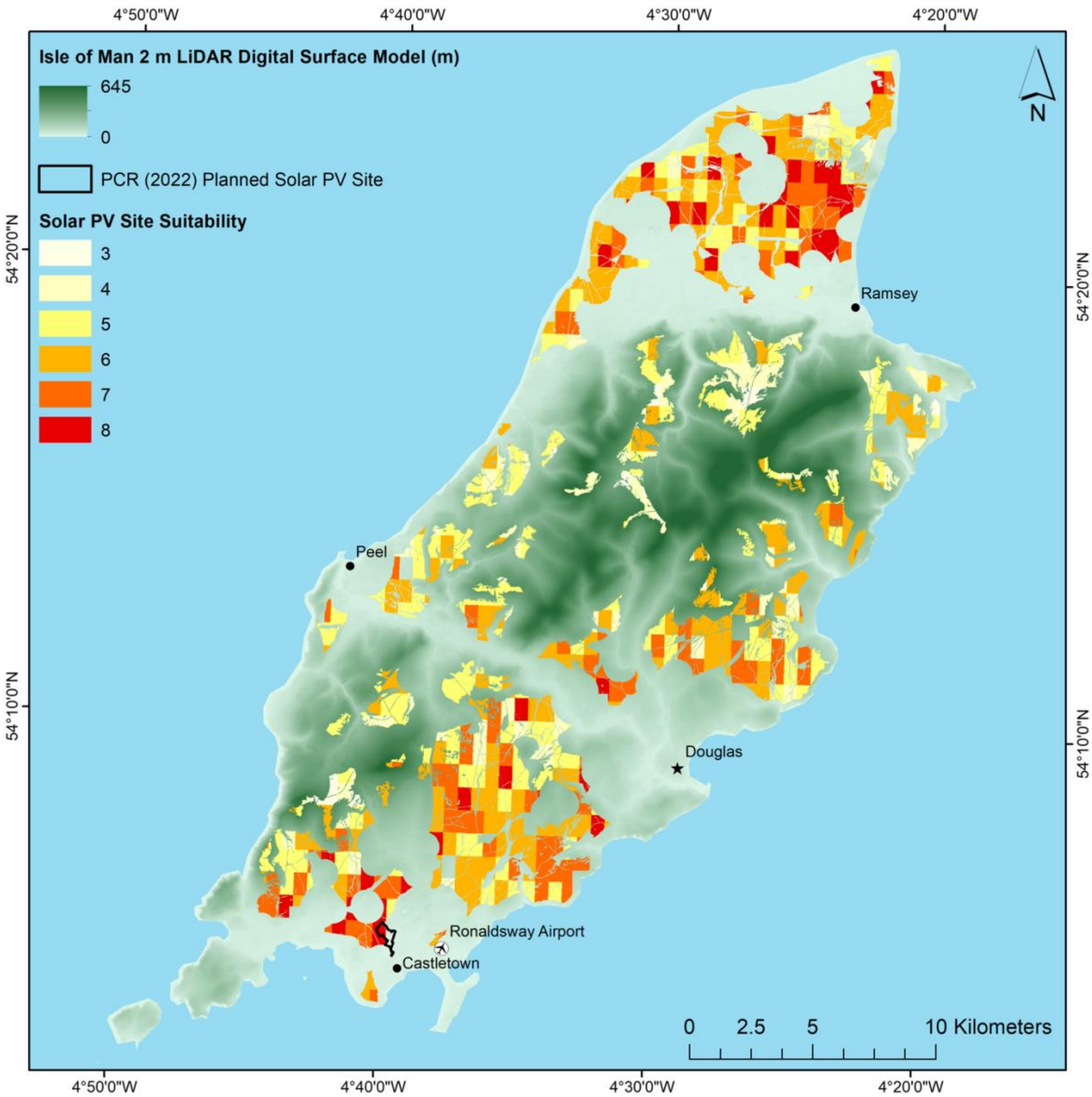


Table 8. IOM suitable area for large-scale solar PV development, according to AHP analysis results and two types of sensitivity analysis (equal weights and no visual impact).

Value Score	AHP			Equal Weights			No Visual Impact		
	Area (km^2)	% of total area	% of suit-able area	Area (km^2)	% of total area	% of suit-able area	Area (km^2)	% of total area	% of suit-able area
1	0.0	-	-	0.0	-	-	0.0	-	-
2	0.0	-	-	0.0	-	-	0.4	0.1	0.2
3	2.2	0.4	1.4	1.1	0.2	0.7	8.0	1.4	3.7
4	18.0	3.1	11.5	8.6	1.5	5.5	31.4	5.4	14.3
5	41.2	7.1	26.4	33.0	5.7	21.2	61.4	10.6	28.0
6	51.0	8.8	32.7	60.6	10.5	38.9	64.5	11.1	29.5
7	30.1	5.2	19.3	43.4	7.5	27.8	38.6	6.7	17.6
8	12.8	2.2	8.2	9.0	1.6	5.8	13.3	2.3	6.1
9	0.5	0.1	0.3	0.1	< 0.1	0.1	1.4	0.2	0.6
10	0.0	-	-	0.0	-	-	0.0	-	-
Total	155.8	27.2	-	155.8	27.2	-	218.9	38.3	-
Total Area 572 km^2									

Figure 13. Theoretical estimation of wind turbine placement for the IOM within onshore wind inclusion zones. Solar PV inclusion zones and the high voltage transmission network are also displayed. Map produced using the *generate points along lines*, *feature vertices to points*, *clip* and *buffer* ArcMap tools.

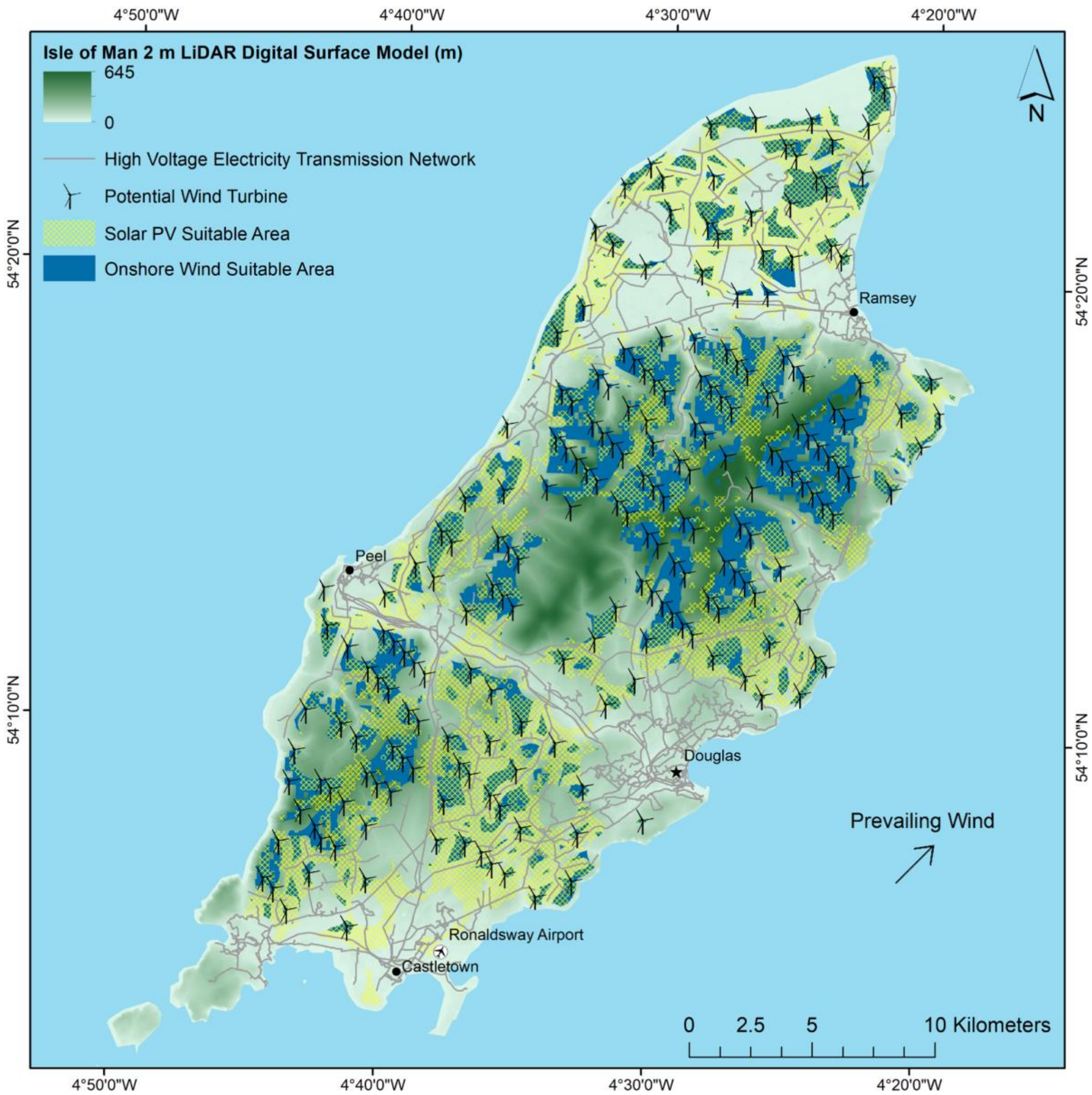
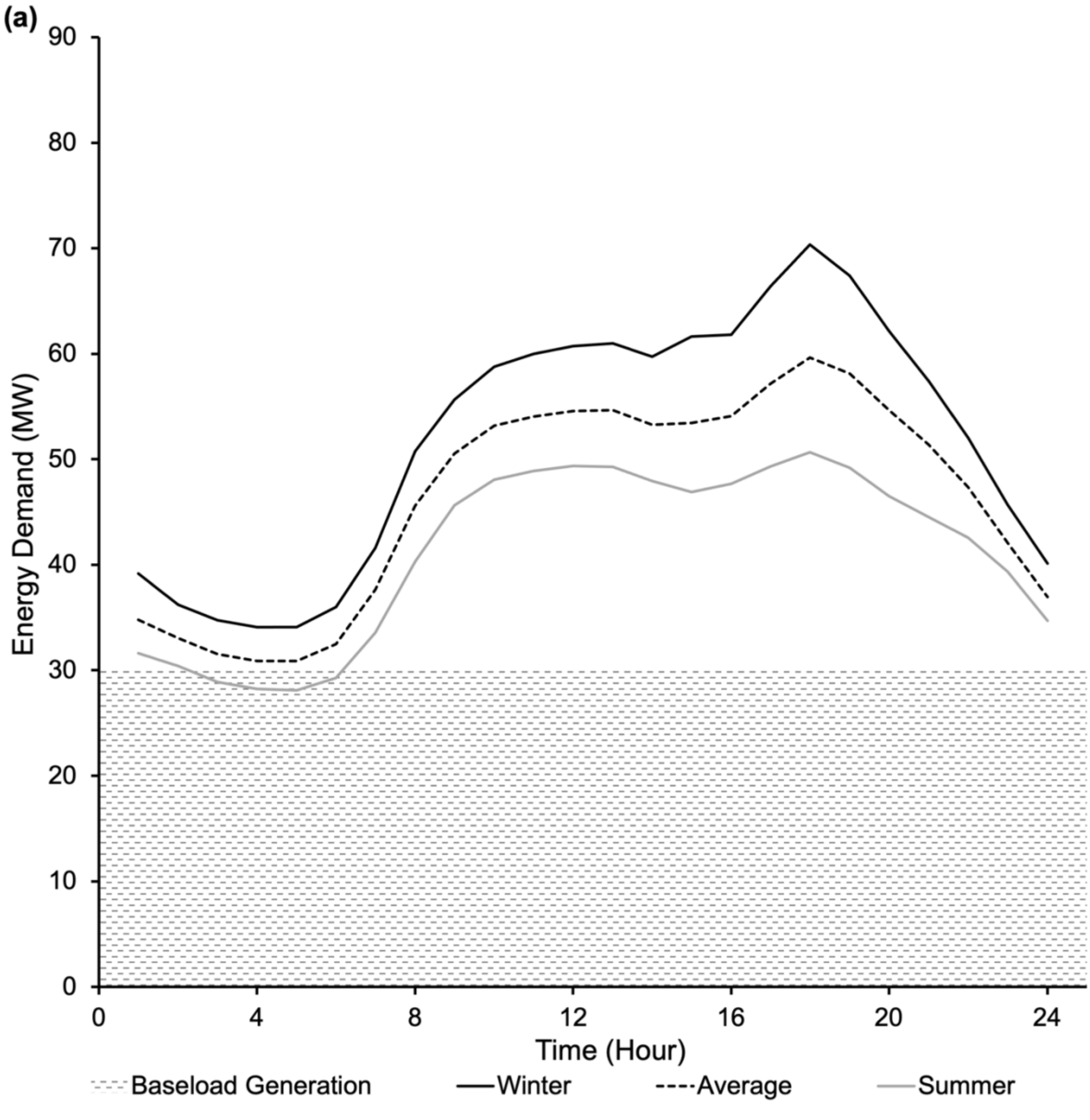


Figure 14. (a) IOM average daily energy demand for the period 2017-2022, showing seasonal differences and the annual average. A baseload (minimum) energy generation of 30 MW is indicated (Manx Utilities, *pers. comm.*). **(b)** IOM average monthly energy demand for the period 2017-2022. Monthly variability is represented through the monthly mean (crosses in the plot), median (line) and the upper and lower quartiles. No outliers were detected (Manx Utilities, *pers. comm.*).



(b)

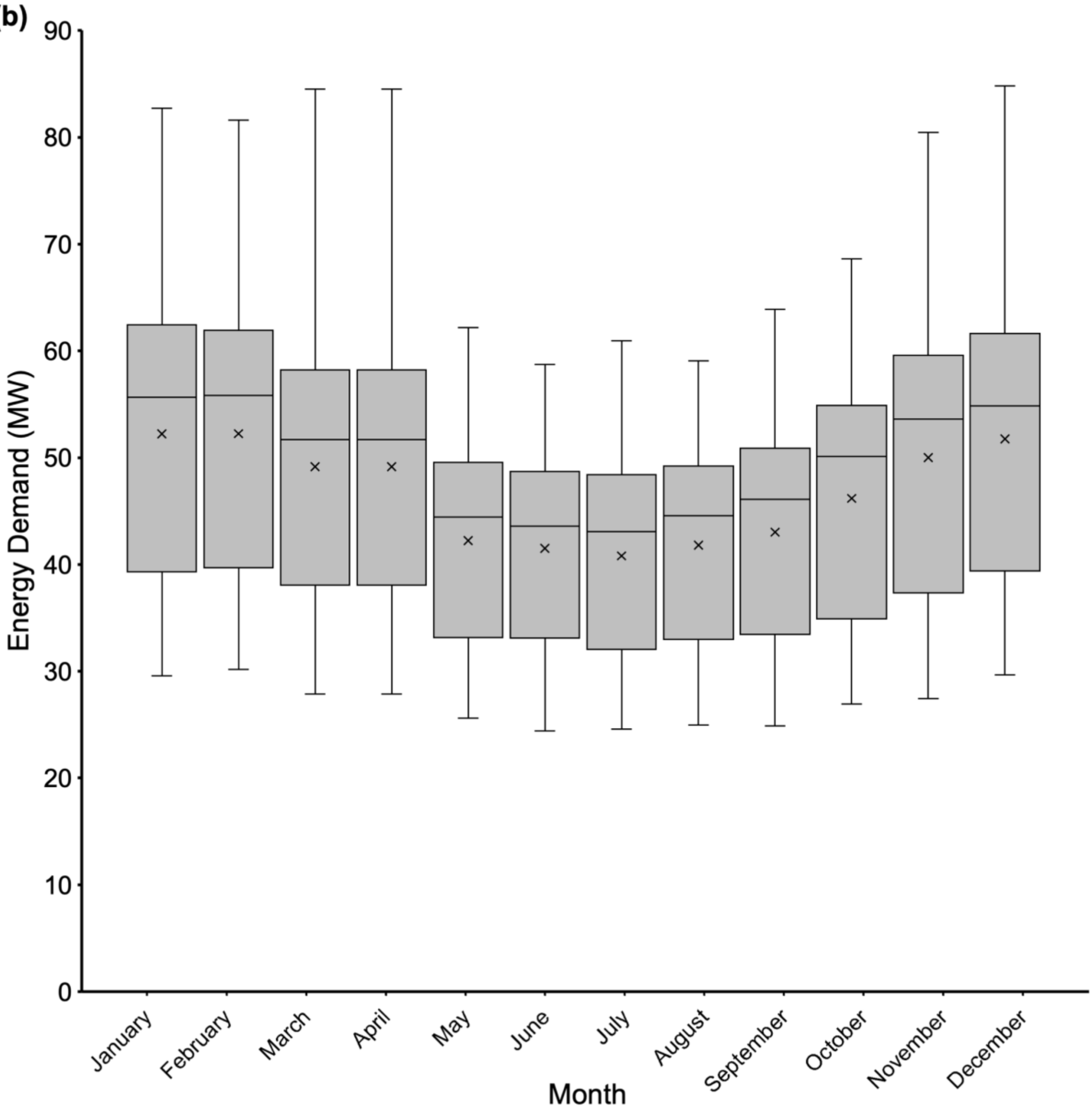
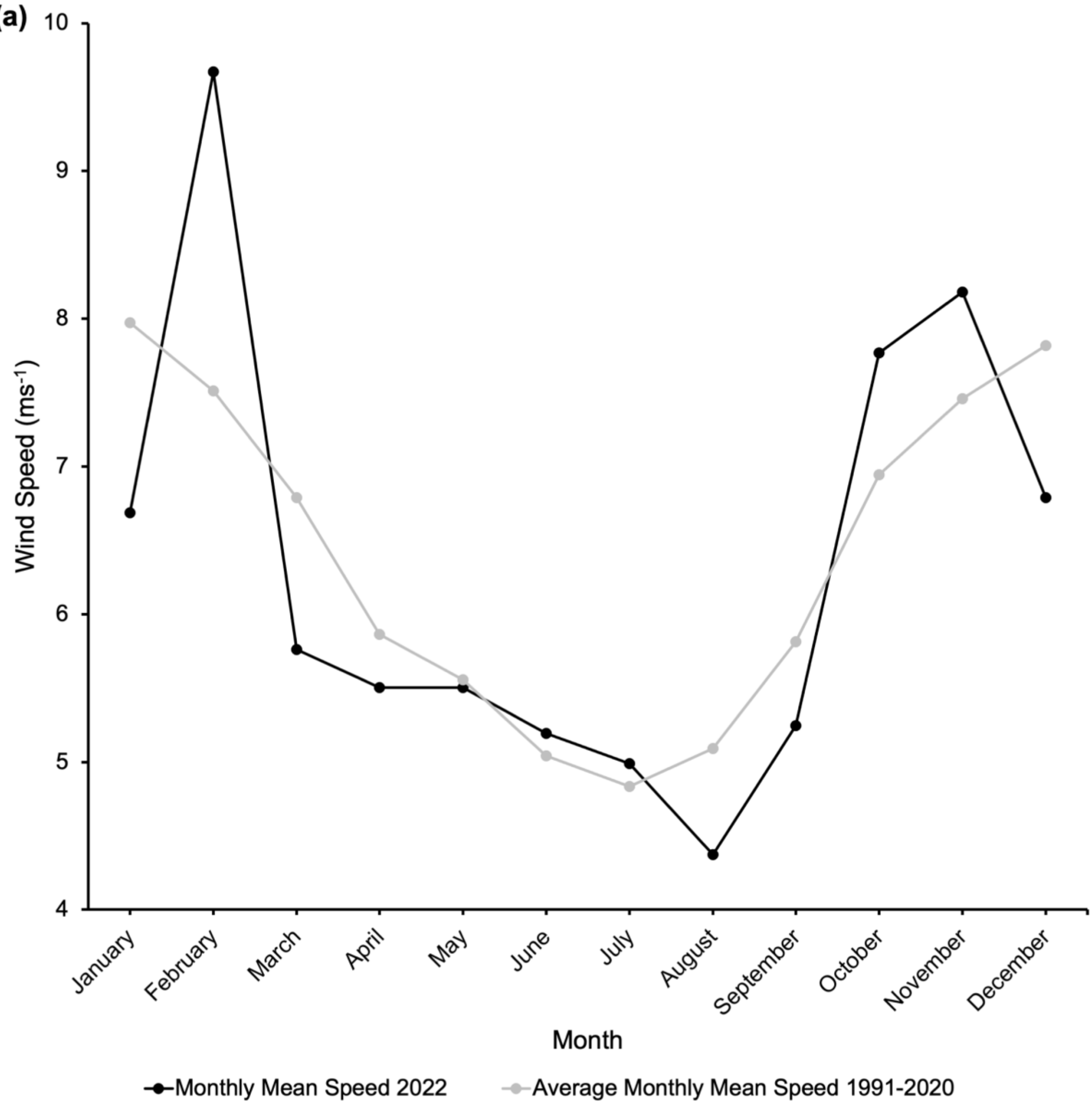
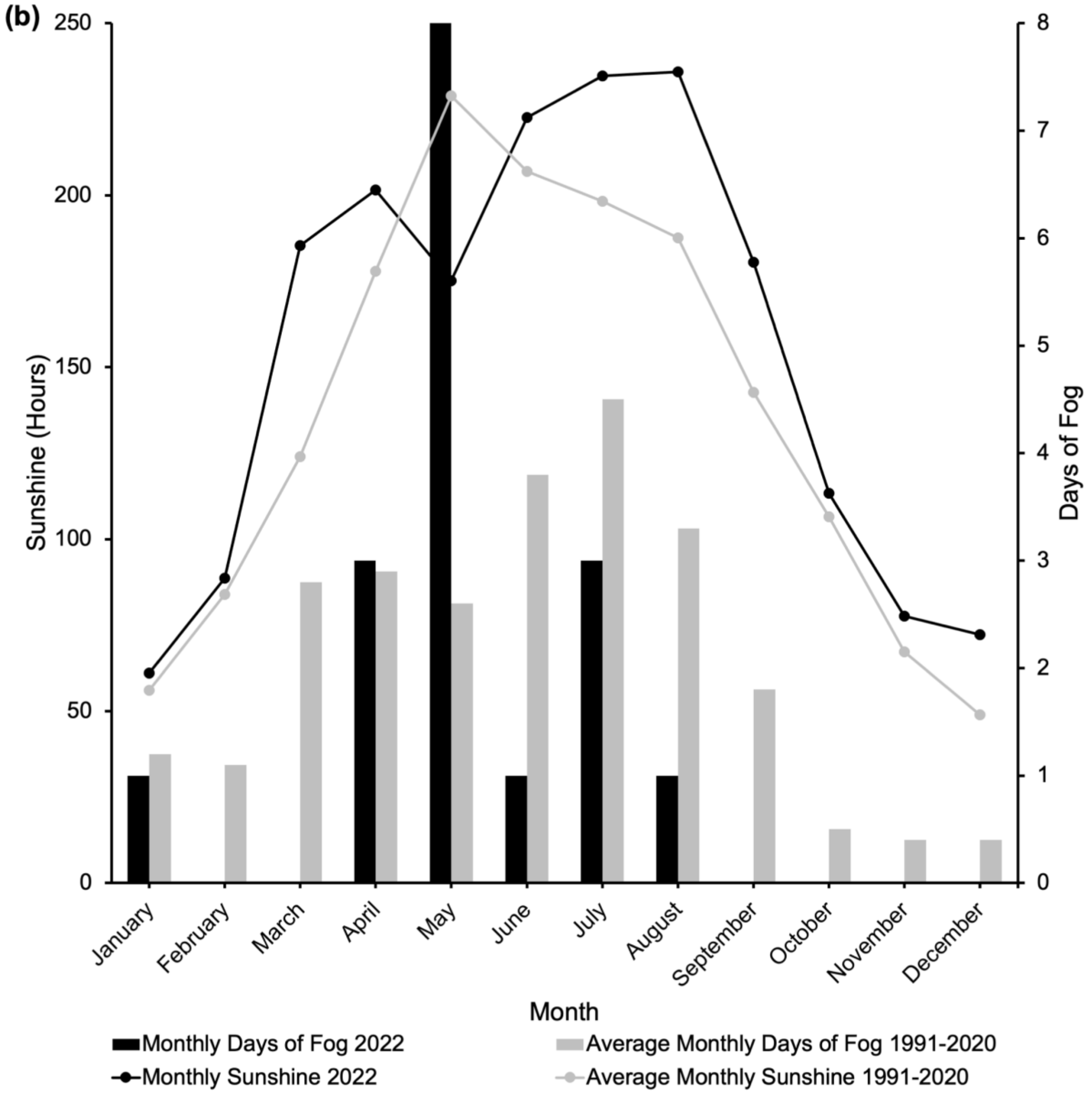

90
80
70
60
50
40
30
20
10
0
Energy Demand (MW)
January
February
March
April
May
June
July
August
September
October
November
December
Month

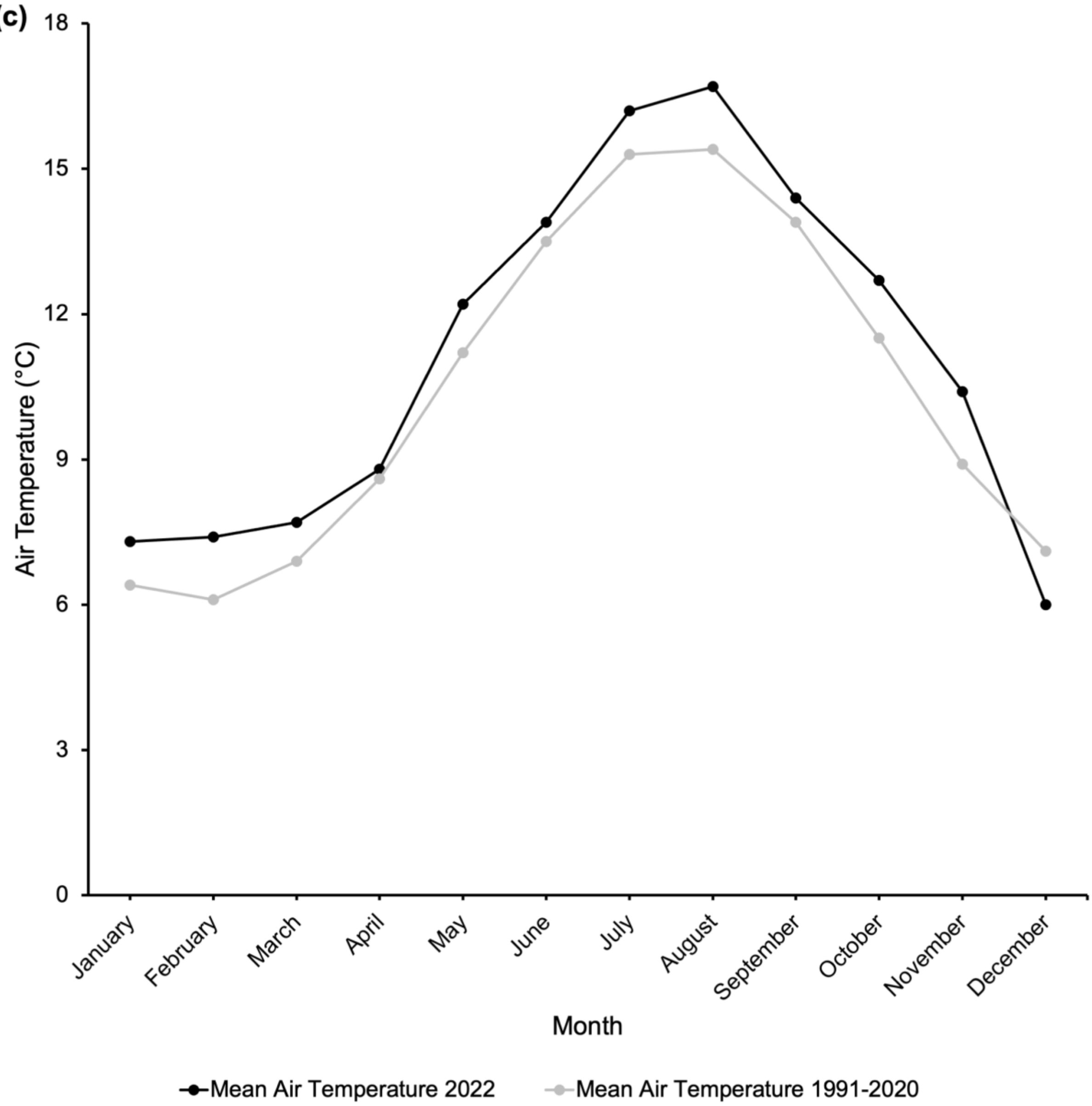
Figure 15. IOM weather data, based on measurements recorded at Ronaldsway Airport Met Office weather station (Met Office, *pers. comm.*). **(a)** IOM monthly average wind speeds (ms^{-1}) at ground level for 2022 compared with the 1991-2020 monthly average **(b)** IOM monthly sunshine (hours) for 2022 compared with the 1991-2020 average, with the monthly days of fog plotted on a secondary axis, also comparing 2022 trends with the 1991-2020 average **(c)** IOM monthly average air temperature (ºC) for 2022 compared with the 1991-2020 average **(d)** IOM annual sunshine (hours) over time. **(e)** IOM annual mean air temperature (ºC) over time.

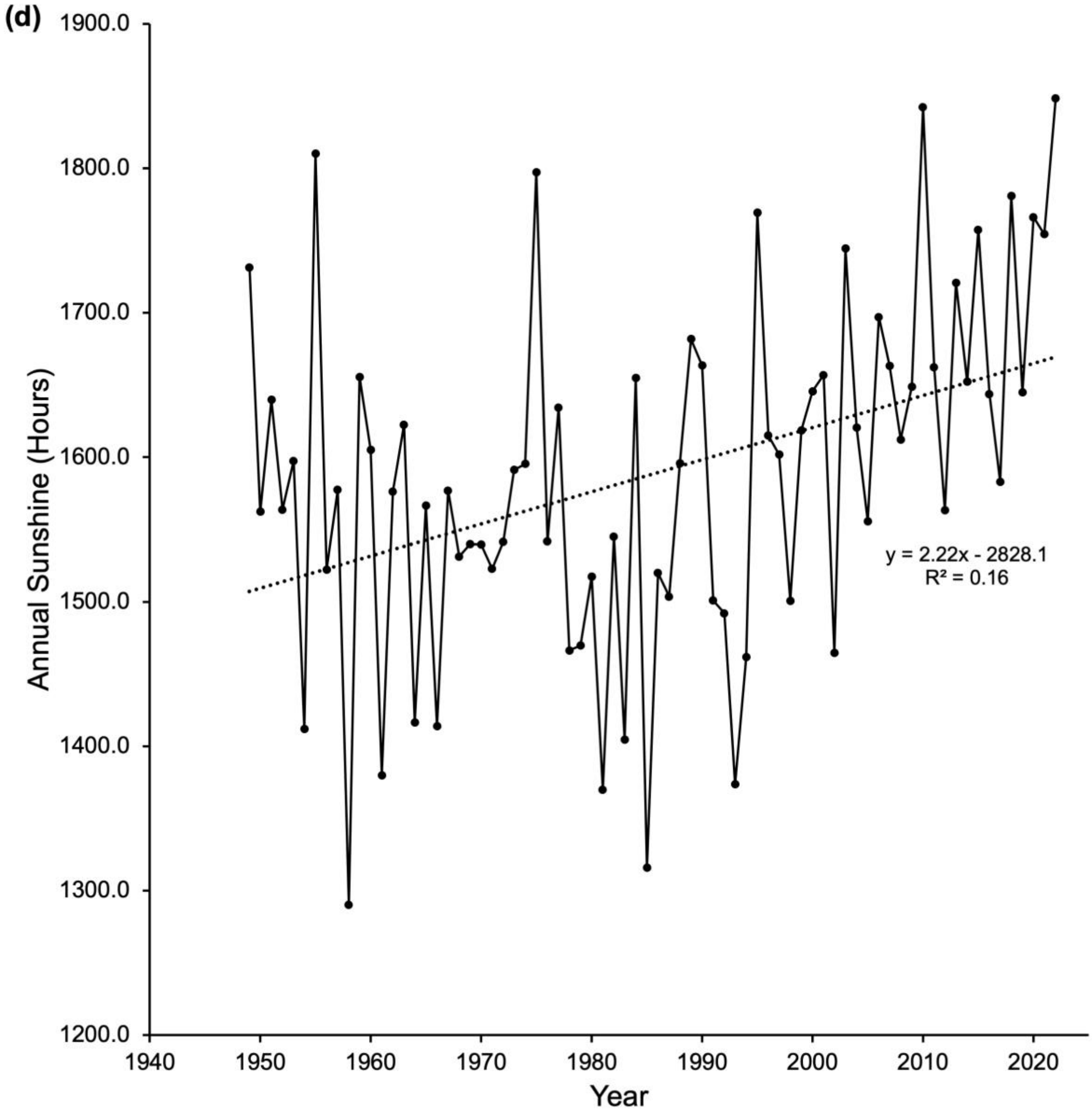
(a)




(b)
Sunshine (Hours)
Days of Fog
250
200
150
100
50
0
8
7
6
5
4
3
2
1
0
January
February
March
April
May
June
July
August
September
October
November
December
Month
Monthly Days of Fog 2022
Average Monthly Days of Fog 1991-2020
Monthly Sunshine 2022
Average Monthly Sunshine 1991-2020

(c)


18
15
12
9
6
3
0
Air Temperature (°C)
January
February
March
April
May
June
July
August
September
October
November
December
Month
Mean Air Temperature 2022
Mean Air Temperature 1991-2020


(d)
Annual Sunshine (Hours)
1900.0
1800.0
1700.0
1600.0
1500.0
1400.0
1300.0
1200.0
1940
1950
1960
1970
1980
1990
2000
2010
2020
Year
y = 2.22x - 2828.1
R² = 0.16

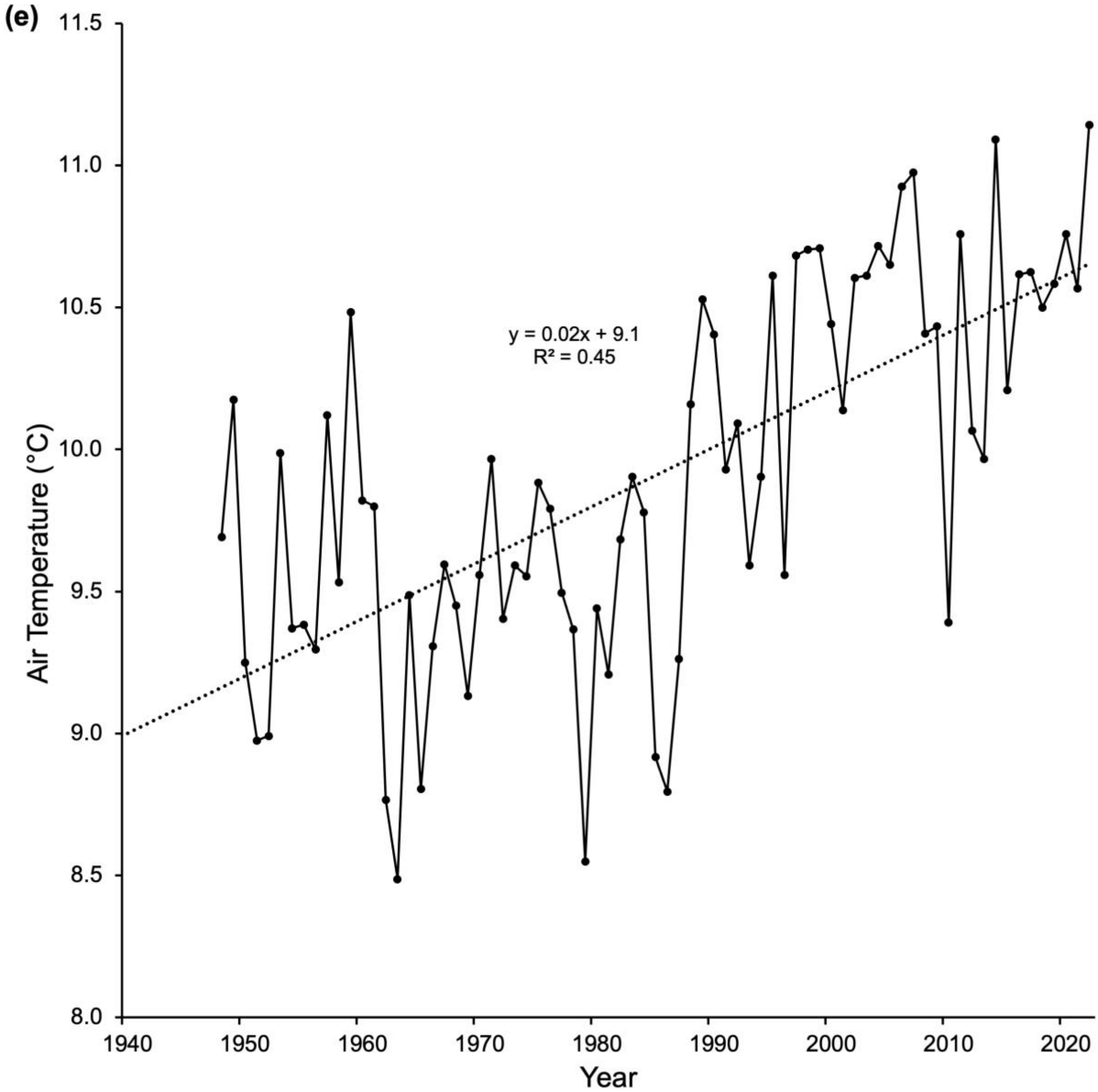
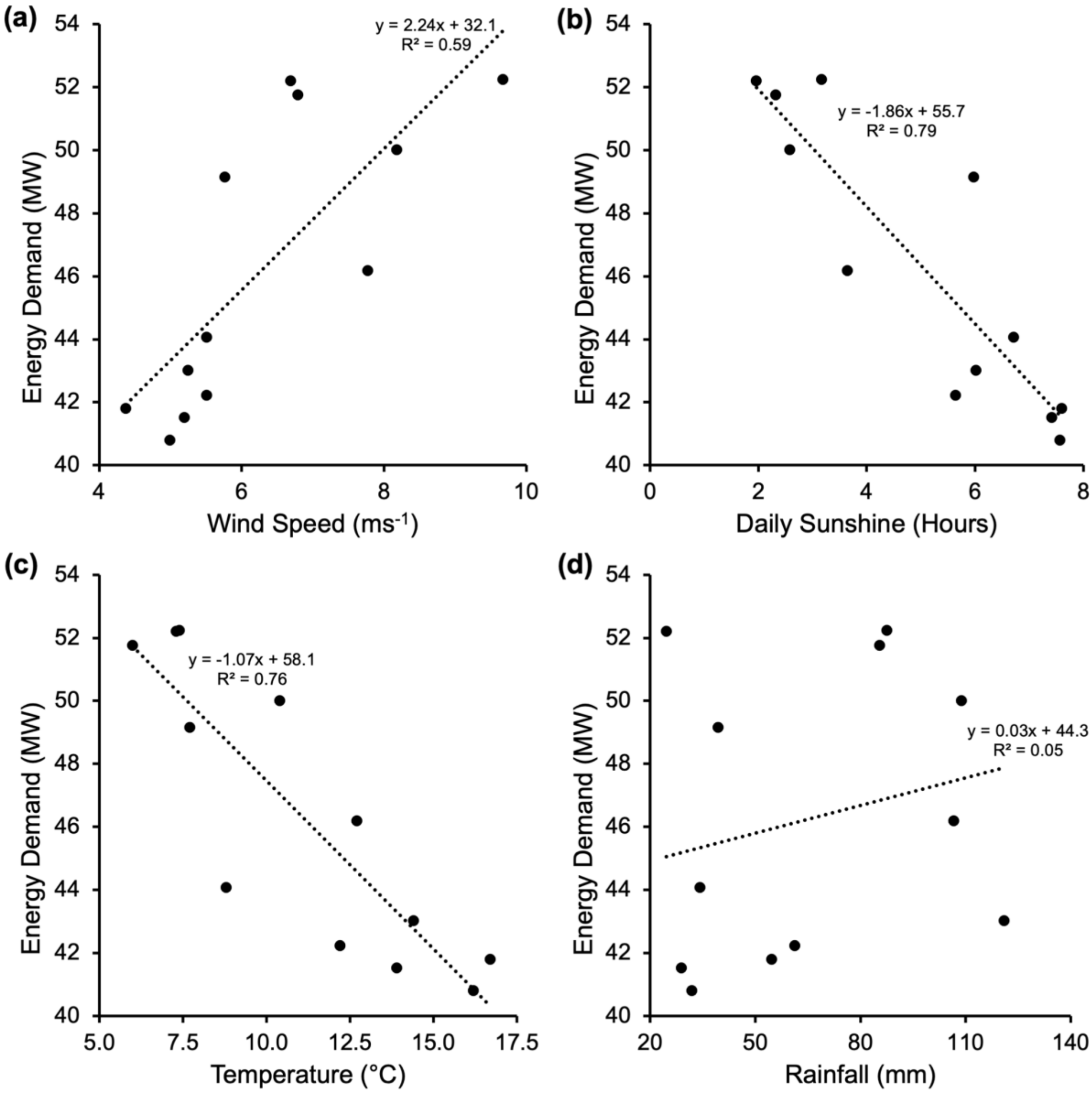

(e)
y = 0.02x + 9.1
R² = 0.45
Air Temperature (°C)
Year
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
1940
1950
1960
1970
1980
1990
2000
2010
2020

Figure 16. IOM energy demand (MW) against **(a)** wind speed (ms^{-1}, $p < 0.05$), **(b)** daily sunshine (hours, $p < 0.05$), **(c)** temperature (^oC, $p < 0.05$) and **(d)** rainfall (mm, $p > 0.05$) (Manx Utilities, *pers. comm.*; Met Office, *pers. comm.*).



DISSERTATION ATTENDANCE SHEET

Student name: Ben Watt   Student ID No: B924334   Advisor: Professor Rob Wilby

Reminder to students: it is your responsibility to arrange meetings with your advisor. You must ensure that this form is signed and dated by your advisor at each meeting.

	Date	Advisor's signature	Meetings notes recorded on Co-Tutor
Milestone 1 – to discuss your research findings before beginning to write up your research; for advisor to complete checklist below. To be held **before the end of S1, week 5**	18/10/22	Robert Wilby	
Milestone 2 – to discuss specific issues relating to data analysis and overall progress; to arrange submission date for a draft chapter and a 2-page annotated dissertation outline. To be held **before the end of S1, week 11**	13/12/22	Robert Wilby	
Milestone 3 – to discuss the draft chapter, dissertation outline and any problems that need to be resolved before submission. To be held **before the end of S2, week 5** The draft chapter and dissertation outline should be submitted to advisor by an agreed date in advance of this meeting. The draft section must not exceed 5 pages.	22/02/23	Robert Wilby	

Students can expect their advisor to read and comment on the draft section in detail and 2-page dissertation outline in general terms as long as they are submitted by the agreed date. Otherwise, what is read is left to the advisor's discretion. Dissertation advisors are not obliged to hold any further meetings with students after this date. Any significant issues relating to your dissertation arising after this date should be directed to the Dissertation Co-ordinator in the first instance.			

Additional meetings should be recorded on the reverse of this sheet.

Checklist: to be signed by the dissertation advisor	**Advisor's signature**
Raw data seen	Robert Wilson
Risk assessment documentation complete and corresponds to work undertaken	Robert Wilson
Ethics checklist complete and corresponds to work undertaken (where appropriate)	Robert Wilson
Questionnaires checked and discussed (where appropriate)	N/A

This Attendance Sheet should be attached at the very end of your dissertation. The dissertation should be submitted electronically on LEARN by **12 noon Friday week 7, Semester 2.**

Record of Additional Meetings

Meetings with your dissertation advisor should add up to a total 1:1 supervision of approximately 4 hours. The distribution and duration of these meetings is largely up to you and your advisor to agree, and will dependent on the type of project you choose and your progress. However, you must have the 3 key milestone meetings before the dates given on the other side of this form.

Meetings additional to the three milestone meetings should be recorded below.

Subject of meeting	**Date**	**Advisor's signature**	**Meeting notes recorded on Co-Tutor (tick)**
Discussion of final touches, formatting and feedback on 5-page draft and outline	21/03/23	Robert Wilby	

Add extra lines if required.