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A decision support system to assess the feasibility of onshore renewable energy infrastructure

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ABSTRACT

This article introduces a new web-based decision support system created for early-stage feasibility assessments of renewable energy technologies in England, UK. The article includes a review of energy policy and regulation in England and a critical evaluation of literature on similar decision support systems. Overall, it shows a novel solution for a repeatable, scalable digital evidence base for the policy compliant deployment of renewable energy technologies.

Data4Sustain is a spatial decision support system developed to quickly identify the feasibility of seven renewable energy technologies across large areas including wind, solar, hydro, shallow and geothermal. A multi-actor approach was used to identify the key factors that influence the technical feasibility of these technologies to generate electricity or heat for local consumption or regional distribution. The research demonstrates opportunities to improve the links between policy and regulation with deployment of renewable energy technologies using novel approaches to digital planning.

Deployed, resilient, cost-effective and societally accepted renewable energy generation infrastructure has a role to play in ensuring universal access to affordable, reliableand modern energy supply. This is central to supporting a concerted transition to a low-carbon future in order to address climate change. The selection and siting of renewable energy technology is driven by natural resource availability and physical and regulatory constraints. These factors inform early-stage feasibility of renewables, helping to focus investment of time and money. Understanding their relative importance and identifying the most suitable technologies is a highly complex task due to the disparate and often unconnected sources of data and information needed. Data4Sustain help to overcome these challenges.

1. Introduction

As highlighted by the United Nations' 7th Sustainable Development Goal and the Framework Convention on Climate Change [1], there is a need to both limit global carbon emissions and enable global access to energy. Multiple societal, policy and technical changes will be required for this to happen. One part of the solution is increased use of locally generated renewable energy, but for this to be effective there is a need for more accessible knowledge of numerous physical, social and financial factors.

The focus of this research is to explore whether a prototype spatial decision support system (DSS) can be developed to map the site-based feasibility of several renewable energy technologies as a solution to problems identified by potential end-users. The problem statement is:

> "As a strategic land use planner (or similar stakeholder) trying to quickly identify at an early stage which, if any, renewable energy

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technology, is the feasible for my area of interest. I need to do this before I invest in a full-scale site-specific study. This is important because relevant datasets required for such an assessment are hard to find and owner by lots of different organisation making it difficult to bring them together, especially for multi technology assessments. This situation makes me feel like discounting renewables as a way of achieving low carbon development given the relative effort and cost incurred on conducting an early-stage feasibility study of renewables."

The potential 'users' of the DSS include strategic land use planners, land owners, developers, land managers and their advisors. The system, called Data4Sustain, assists with assessing where renewable energy might be feasible through the use of multi-criteria decision analysis, mapping and visualisation. The users identified are those involved or support the design and installation of renewable energy technologies (RET), including characterising natural resource and constraints in the context of the regulatory landscape.

The 5-stage framework adopted for this research is shown in Fig. 1, the diagram illustrates the sequence and iterations followed from problem statement to a prototype DSS.

The multi-actor approach taken here involved the researchers, the private sector and policy and decision makers, enabling a critical evaluation of the key factors that attract and discourage six types of renewable energy technologies (RET). The assessment was used to create a rapid spatialDSS that can shortlist candidate RETs at any site or highlight sites that are more or less suitable for a particular RET. The system is designed to speed up early-stage site selection and development of RETs, thereby supporting the transition to a low carbon future. The seven RETs included in the DSS are small to medium-scale and large-scale wind turbines, solar, small-scale hydropower ,water source heat pump, horizontal closed-loop and vertical open-loop groundsource heat pumps, each of which generate electricity to enable infrastructure or heat for local consumption or distribution.

The DSS has covers three areas of England and has demonstrated the applicability of the work to inform renewable and sustainable energy generation practice in other parts of the UK and beyond.

This paper is structured as follows; in Section 2 is presented the regulatory context enabling the deployment of onshore RET; in Section 3 are described the methods for data selection, collection and pre-processing; in Section 4 are presented the results of using D4S to assess the installation of ground source heat pumps, wind turbines and solar photovoltaics, the discussion includes the reporting options available from the tool and the opportunities for improvements; Section 5 presents the conclusions.

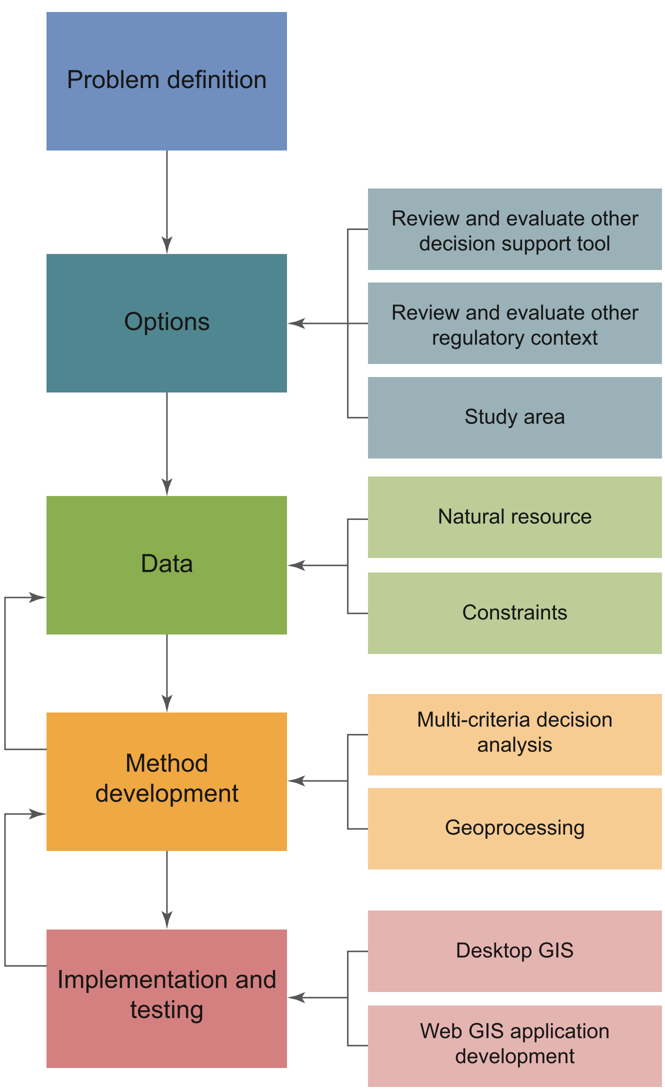

Fig. 1. Decision support system framework.

2. Regulatory context, decision making and decision support systems

In this section, a review is presented of key policy and regulatory enablers and constraints that have helped shape up the market, availability and deployment of onshore RET in England, UK. The impact of these have informed the tool presented in subsequent sections.

2.1. Climate change and universal energy access

The Intergovernmental Panel on Climate Change (IPCC) Summary for Policymakers within their Sixth Assessment Report states that "*It is unequivocal that human influence has warmed the atmosphere, ocean and land*" [2]. The same document goes on to note that "*limiting human-induced global warming to a specific level requires limiting cumulative Carbon Dioxide (CO_2) emissions, reaching at least net zero CO_2*". The IPCC recognised the importance of renewable energy production as part of the solution to mitigate global warming [3]. Their report provided underpinning evidence for The United Nations Climate Change Paris Agreement, a binding policy that aimed to limit global temperature rise this century to below 2 °C, ideally 1.5 °C, above pre-industrial levels [4].

However, this immediate need to reduce CO_2 emissions is in conflict with the need to continue to generate and distribute energy as stated by the United Nations Sustainable Development Goal No. 7 "*access to affordable, reliable, sustainable and modern energy*" [1]. Deployed, resilient, cost effective and societally accepted renewable energy generation infrastructure is needed to deliver this, and this is dependent on good knowledge of a number of site-specific factors.

The successful development of renewable energy is dependent on many factors, including resource availability, engagement with the local community, finances and physical and regulatory constraints. Policies and regulations are key enablers of this process, but do not alone provide the necessary ingredients to inform decision making for early-stage renewable energy feasibility assessments, which is the gap this work is fulfilling.

2.2. On-shore renewable energy in England, UK

The UK is committed to a transition to net zero by 2050, compared to 1990 levels by 2050 [5].

In 2019, UK renewable energy generation reached an all time high of 36.9% (119 TWh) [6], the first-time the proportion of renewables exceeded fossil fuels and demonstrating the UK is already making progress towards the net zero target.

To tackle current challenges, the option of decentralising energy generation has been considered, which means to de-escalate and redistribute energy generation within the territory [6].

One of the challenges in this path of decarbonizing the energy system is to integrate renewable sources of energy without affecting stability, i.e., by matching demand and supply of energy [7]. The Government and Ofgem's policies to reform the energy system in this aspect are contained within the Transitioning to a Net Zero Energy System white paper [8] which aims to facilitate the transition to a smarter and more flexible energy system.

A smart and flexible energy system is considered to be essential in order to achieve the proposed net zero climate goal and provide affordable energy costs [8]. The kind of RETs in this paper are allocated within the category of flexible generation, which are low carbon peaking plants or intermittent generation like solar or wind farms. Although these technologies are becoming more affordable due to the reduction in investment costs, there are still economic and technical challenges to solve, like the integration of small, medium or large intermittent RETs into the grid [9].

The Energy White Paper: Powering our Net Zero Future [6] states that flexible generation would facilitate the decentralisation of the energy systems, allowing the integration of large, medium and, especially, small generation sites across the country. The Government projects the increase on energy demand in the transition to decarbonise the energy sources; it is expected that this *"This change necessitates a very different approach, and not just because the energy system must* support *the deployment of clean energy technologies. It will also have to adapt to a world in which energy is far more decentralised" (p. 66). Demand will be satisfied as much by local solutions as by a nationally organised and operated system" (p. 111)*. As a result of this, in the policy paper British Energy Security Strategy, the government pledges to support flexibility for both generators and users in all its forms [10].

Policy and market requirements will drive both deployment of existing RETs and the development of new generation and carbon capture/emission reduction technologies. Deregulation of the energy markets also encourages RET development, as it provides new opportunities for small scale generation capacity to contribute to the national grid networks [11].

2.2.1. *Micro, small and large-scale installations*

Policies for the deployment of renewable energy installations depend on the scale measured by the installed capacity. Small-scale installations were defined in UK domestic regulations as those with a declared net capacity up to 5 MW [12] and amended by the Feed-in Tariffs (Amendment) (No. 3) Order 2015 [13], while microgenerators consist of installations of declared net capacity up to 50 kW. Above this are the large-scale low carbon electricity generators.

The Smart Export Guarantee Order 2019 [14], Section 4.1 of the Energy Act 2008 [15] regarding modifications to the standard conditions of energy supply licences, constitute the regulatory framework for small-scale low-carbon electricity generators. Large-scale low-carbon electricity generators deployment is driven by the Contracts for Difference (CFD) [16].

Regulations to allow generation and uptake of energy from renewable sources from not only large but also micro and small-scale installations, are important to increase the ability of the energy system to respond to changes in demand as part of the flexibility programme [8,9]. Regulations for licensing, installing, and connecting to the grid are factors that impact the deployment of renewable energy technologies, as has been observed with the impact on the adoption of photovoltaic systems by the reduction on Feed-in Tariff incentives [17,18]. Crucially, planning policies and regulations have a direct impact in the deployment of RETs within the territory. The location site of renewables installations is fundamental in influencing the business model for an investment that can make use of the policies promoting small, medium, or large-scale renewable energy technologies (RETs). According to Maditereza and Bansal [19], finding optimum locations, size, and maximum penetration levels for distributed generation is central to the deployment of RETs.

2.2.2. *Locating sites for renewable energy installations*

A challenge in identifying suitable locations, is that different RET installations have different relevant criteria. Traditional energy generating capacity is based on large industrial facilities located close to the source of fossil fuels, transport infrastructure and cooling water. In contrast, with the exception of large-scale hydroelectric plants and offshore wind farms, renewable energy resources are typically of smaller kW capacity, decentralised and geographically widespread, requiring grid connections/and or storage. Small to medium scale RET facilities rely on the identification of sites where their suitability for successful generation is dependent on site-specific environmental and planning factors which influence generation output. Distributed power generation using RETs can contribute significantly toward the UK power requirements, but it is unlikely that any single technology will in itself be sufficient or provide appropriate levels of power resilience.

The Planning for a Sustainable Future White Paper [20], outlined the National Policy Statements and sought to improve the town and country planning system. There are however efforts to publish an updated white paper and the consultation Planning for the Future [21] has been launched. Planning for the Future provides the current Government's aspiration for major planning reform. This includes a strong digital component of plan making and delivery, which features in the first parliamentary reading of the Levelling Up and Regneration Bill 2022.

Location factors link to the English planning policies around place making and renewables including new proposals to 'zone' suitable locations for specific development scenarios in the Planning for the Future consultation [21]. The consultation proposes reforms regarding energy efficient buildings and their role in net zero and notes a desire for spatially-specific policies to improve public access where renewable energy could be accommodated. Overall, the consultation lacks explicit recognition of onshore renewables policy in forthcoming planning reform. On a more positive note, the proposals support a shift from a paper-based planning system to a data-driven one. This is expected to result in an increase in the accessibility, availability and reliance on spatial data and digital decision support systems for land use planning and management [22].

The National Planning Policy Framework (NPPF) [23] sets out the planning policies for the government in England. It promotes increased "use and supply of renewable and low carbon energy and heat" [par. 155] as part of the transition to a low carbon future. It encourages plans to identify "suitable areas for renewable and low carbon energy sources" [par. 155] and identify opportunities for development and low carbon energy sources to be co-located. There is positive support for community-led initiatives for renewables including those in neighbourhood plans. In paragraph 158 is defined that "when determining planning applications for renewable and low-carbon developments" [par. 158], there is no requirement for the need for the renewable or low-carbon energy to be demonstrated as "even small-scale projects provide a valuable contribution to cutting greenhouse emissions" [par. 158]. There are limitations to the support for renewables in the NPPF, for example, if located in the Green Belt, very special circumstances will need to be demonstrated. Thus, local planning requirements are an important part of deciding feasible locations for RET installations.

Similarly, the Renewable and Low Carbon Energy Guidance [24] provides support on how local planning authorities can develop a positive strategy for delivery of renewables and low carbon energy and support community led initiatives. It comments on how planning authorities can identify suitable locations and highlights the importance of identifying opportunities to develop decentralised energy, emphasising the need to get the *"right land uses in the right place"* [25] *(par. 19)*.

2.3. Decision making for renewables

The global and national drive towards net zero creates a policy environment which is supportive of increasing development of renewables. Moreover, the increase and volatility of energy prices have been accelerating the commitments to deploy low carbon energy systems in Great Britain [10]. In addition, the support for flexibility and decentralised generation has increased the scope for renewable energy [11]. Identifying suitable locations to develop renewable energy resources requires careful evaluation of the physical and policy constraints [26]. Determining if a site or area is feasible for RETs involves significant investment of both time and money where the balance between social, economic and environment constraints defines whether renewable energy projects go ahead. Failure to consider these factors properly can cause significant project delays or cost overruns [27].

The Local Planning Authorities are responsible for applications for renewable and low carbon energy developments of 50 MW or less installed capacity [28] while large scale developments are considered by the Secretary of State for Energy [29]. From the local planning authorities' perspective, the aim of permitting RETs is to achieve sustainable development [29]. National Policy Statements inform the decisions of the Secretary of State regarding the development of biomass and waste production in addition to offshore wind technologies [29]. The National Policy Statement for Renewable Energy Infrastructure [30] is a guide for the Secretary of State to assess large energy infrastructure, but also serves as an aid for Local Planning Authorities regarding medium or small RETs, and the site adequacy and sustainability. Failure to comply with National Policy Statements could cause the rejection of the application by the Secretary of State or the Local Planning Authority [29]. There is scope for national policies to be enhanced to encompass a wider variety of onshore technologies, linking to more recent aforementioned white papers on energy and planning.

Regarding renewable or low carbon energy developments with installed capacity up to 50 MW, Local Planning Authorities in England must consider applications in consideration of the development plan, the Planning Act 2008 [29], the Climate Change Act 2008 [31], and the National Planning Policy Framework [23], among others. The aim is to support the sustainable development of green energy whilst protecting the local environment [23].

According to Renewable and Low Carbon Energy Guidance [25], Local Planning Authorities must develop and maintain a Local Development Scheme to promote the deployment of renewable and low carbon energy, considering the National Planning Policy Framework [23]. Local Plans should contribute to the sustainable development, be unambiguous and "be shaped by early, proportionate and effective engagement between plan-makers and communities, local organisations, businesses, infrastructure providers and operators and statutory consultees" [22,24] (par. 16), among others. The provision of energy is identified as a strategic policy and is therefore considered a priority that must be addressed in the development plan by establishing sufficient land-use designations and allocations identified on a policies map to meet the strategic needs of the area [23]. Crucially, the preparation and review of the policies must be made using "relevant and up-to-date evidence", in order to be considered "sound" [23] (par. 31).

Planners, landowners and developers need digital decision-making tools to evaluate the multiple criteria which affect the location of RET installations.

2.4. Approaches to decision making and decision support systems

Decisions on siting RETs need to take account of numerous factors and be based on evidence. Avoiding subjective judgment in these decisions requires a systematic and repeatable approach to facilitate consideration of multiple, often conflicting geographically constrained variables. These complexities can be addressed using a combination of Problem Structuring Methods (PSM) and Decision Analysis (DA) [32]. Problem Structuring Methods facilitate engaged and structured conversations to synthesise common understanding of challenging situations, methods may be as simple as a SWOT analysis or more complex and academically focussed like expert elicitation. A combined PSM and DA approach can be used to develop bespoke Decision Support Systems (DSS) to achieve transparency and replicability. DSSs are most commonly computer-based tools that support, enforce structure and organise decision making activities [33]. Sprague (1980) [34] defines a well designed DSS as follows:

a. Aimed at less well structured, underspecified problems typically faced by upper level managers;
b. Combines the functions related to assessing and retrieving data with the utilisation of models or analytic techniques;
c. Focused on features which make them interactive and easy to use by non-computer-proficient people; and
d. Emphasises flexibility and adaptability which accounts for how and where users make decisions.

Multi-Criteria Decision Analysis (MCDA) is an ideal method to manage the complexities of land use decision making [35], especially when used in conjunction with Geographic Information System (GIS) [22]. MCDA is a group of methods commonly used across a range of disciplines including; environmental sciences [36], brownfield redevelopment [22], construction [37], medical and veterinary science [38], real-estate and land management [26], climate science & policy [39] urban energy system planning [11] and a great number of others [40, 41]. A review conducted by Strantzali and Aravossis (2016) [42] recognises that the choice of method largely depends on the preferences of the decision-maker and analyst i.e. there's often no right or wrong method. This is a point supported by Hammond et al. (2021) [22], who highlights a gap and need for early-stage DSSs in urban planning and development.

2.4.1. Review of decision support systems

A review of the academic and grey literature was conducted to identify existing tools and whether they have the potential to address the problem statement written for this research. A search of the academic literature using the Scopus bibliographic database returned 206 publications. The search was focused on title, abstract and keywords with search string: ("renewable energy" OR renewable* OR solar OR wind OR geothermal) AND ("Decision Support Tool*" * OR "Decision Support System*" OR software* AND GIS).

One review of note was published by Picchi et al. *2019* [43], who's work was a systematic review of renewable energy decision support systems. They characterised the systems they reviewed into four typologies: 1) social attitude: studies that focus on what people think about renewable energy development, what their attitude is with regard to landscape changes, and what attitude they have towards improving their surroundings through RET; 2) impact assessment: studies that assess the impact of an RET on the environment and landscape; 3) planning: quantitative and qualitative studies evaluating land-use development scenarios using expert methods and datasets at local and regional scales; and 4) integrated planning: studies examining the conflicts and tradeoffs between different land use demands.

The wider 206 publications returned by the Scopus search were sorted for relevance, which reduced the number down to 89 to represent those DSSs that focus on assessing the feasibility of RET. A review of these publications show the following trends:

- Over time the frequency of decision support tools/systems publications has steadily increased. There was a spike in publications per year in 2015, increasing again from 2018 to 2022;
- The majority of tools focus on site selection assessing for a single resource type (n = 67) e.g. solar [44], wind [45] or geothermal [46]. A smaller number of studies were designed to assess multiple RETs

(n = 17) e.g. Mwanza and Ulgen, 2020 [47] consider wind, solar photovoltaic, biomass, and hydropower for electricity generation; Bracco et al, 2018 [48] considers solar, wind alongside cogeneration
- Wind (n = 19) and solar (n = 26) are the most common focus for single RET studies, other single resource studies included geothermal, biomass energy, wave and tidal. Studies evaluating areas for solar energy include: Sánchez-Lozano et al., 2014 [44], Sun et al., 2013 [49], and Huld et al., 2017 [50]. Studies evaluating for wind energy include: Aydin et al., 2010 [51], Simao et al., 2009 [52], and Mekonnen and Gorsevsk, 2015 [53];
- The majority of studies (n = 54) utilise GIS methods (i.e. proximity analysis, suitability modelling) for spatial analysis of technical potential (i.e. natural resource availability and deployment viability) for renewable energy technologies for a given area;
- Several tools consider social constraints for renewable energy resource allocation (n = 16). For example, the highly-cited Aydin et al., 2010 [51] include criteria to assess the impact to the local community, impact of noise, and visual blight on the landscape;
- Some tools have been designed to act as structuring for stakeholder; discussion/participatory methods (n = 13).e.g. González and Connell, 2022 [54], and Mekonnen and Gorsevsk, 2015 [53];
- Multi-criteria decision analysis is often used to support the generation of results in these tools (n = 17) e.g. ELECTRE [44], Weighted Sum Model [55], and TOPSIS [56];
- Fuzzy and hybrid methods for dealing with ambiguity in decision-making also feature in the search results (n = 9). Fuzzy hybrid methods used include: Fuzzy Analytical Hierarchy process [57], Fuzzy Logic-GIS [58], fuzzy best worst method [59]; and
- The use of Web-based applications and WebGIS to host an RET selection DSS is also seen in the literature (n = 5).

A review of the grey literature using the Google search engine found 22 decision support systems. Of these publications, the following trends were noted:

- A large number of DSSs are freely available and publicly accessible (n = 19);
- Many of the systems were created by public agencies (i.e. United States National Renewable Energy Laboratory) and/or education sector [60–62], with a smaller number of private sector developments [63–65];
- The geographical scale of the DSSs found were global or multinational (n = 13), Nation specific (n = 9); and
- There was a broadly equal split between multiple RETs and single RET with most hosted on web-based rather than desktop software. The principal resource types evaluated by the systems were solar and wind RETs. For Example, Googles Project Sunroof [66], the PV*SOL Online tool [67], and World Bank Groups Global Wind Atlas [61].

The functionality of these decision support systems found required the user to identify an area of interest through a WebGIS, which was then used to show RET suitability maps created using various modelling techniques from a wide variety of data sources. For example, the Global Wind Atlas [61] was created from data from the European Centre for Medium-Range Weather Forecasts (ECMWF) considering the topography, orography, surface roughness, and obstacles to determine wind speeds.

The key opportunity noted for new research following a review of the literature is for a web-based, user-led DSS that evaluates multiple RET including both above and below ground technologies and cover planning and policy constraints.

2.5. A new decision support system for locating RETS

To complement and demonstrate how digital tools can assist with policy implementation and renewables deployment, the authors developed an innovative and research prototype decision support system called Data4Sustain (D4S). D4S is a web-based spatial decision support system for the feasibility assessment of seven RETs. The system is designed for end users evaluating sites (e.g. site owners, developers and Local Authorities) but can also be used by policy makers or vendors to exploit or delineate other suitable sites for each renewable technology. The tool evaluates resource, constraints and feasibility for small to medium scale wind, large scale wind, solar photovoltaics, small scale hydro and vertical and horizontal ground source heat pumps. D4S uses MCDA to derive mapped outputs which are presented in a bespoke Web GIS as fully attributed choropleth maps with a detailed dashboard and reporting functions.

D4S could be used in the process of preparing Local Plans for examination by the Secretary of State, in which the soundness of the plan will be assessed. Evidence is required to justify the reasoning behind the allocation of sites for development, following a method that is logical and consistent [68]. There is an acknowledgement of the challenges posed to local authorities, who are encouraged to engage with industry experts that can help identifying siting requirements in order to assess the deployment of RETs and, more importantly, its cumulative impact in the environment [25].

3. Materials and methods

The D4S spatial decision support system was jointly developed by Land Quality Management Ltd, the British Geological Survey, Nottingham Energy Partnerships (NEP) and the University of Nottingham (UoN). The technical basis of D4S was informed by technical and policy workshops with specialists from LQM, BGS, NEP and UoN who designed and implemented a set of methods for data selection, collection and pre-processing followed by multi-criteria decision analysis. These methods were implemented using ESRI ArcMap Version 10.1 and bespoke Web GIS client application. NEP produced the initial scoring for each renewable energy technology; LQM and BGS developed the input data for above and below ground RETs respectively. BGS created the WebGIS using an agile software development approach, comprising use case and user experience research, wireframe mock-ups and software development sprints.

This section focuses on three of the seven RETs: Vertical open loop ground source heat pumps, large wind turbines and solar photovoltaics. These were selected as they demonstate the breadth of the tool for above and below ground technologies.

3.1. RET selection and study area

Seven RETs were evaluated to identify the key factors affecting resource potential, planning/environmental constraints and overall feasibility. The RETs evaluated were:

i. Small to medium scale wind (≤100 km and 18 m generation hub height?);
ii. Large scale wind (>100 kw and 45 m generation hub height);
iii. Solar photovoltaics (solar farm);
iv. Small scale hydro;
v. Water source heat pump;
vi. Open loop vertical ground source heat pumps; and
vii. Closed loop horizontal ground source heat pumps

These RETs were selected because they are commonly deployed in both domestic and commercial settings at different scales, and are subject to geographical constraints. The RETs qualified for feed-in tariffs [12,13] (scheme now closed to new installations) or the Renewables Heat Incentive [69]. The seven RETs are divided into two groups, above and below ground where the former produce mainly electricity or, in the case of WSHP, heat from wind, water and solar and latter produce low grade heat from the ground for use in buildings.

The viability of RETs is affected by multiple factors is summarised as follows:

1. Natural resource availability;
2. Technically accessible resource;
3. Physical environment constraints;
4. Planning and regulatory constraints;
5. Legal constraints;
6. Economic viability;
7. Deployment viability (supply chain); and
8. Regional ambition – target setting and incentives.

D4S is designed to addresses the first four stages. These stages tend to feature at the start of the site assessment and feasibility studies. Legal constraints, economic and deployment viability and regional ambition are not considered to be part of an early-stage assessment but rather a detailed desk-based study conducted once the initial feasibility work has been undertaken.

For each RET, the factors affecting feasibility were identified the authors, guided by NEP. Collectively the group's expertise covers renewable energy policy, planning and installation, geoscience, land use planning and geoprocessing.

The D4S study area was the West Midlands, Nottinghamshire and Derbyshire, UK (Fig. 2).

To illustrate how D4S has been produced, this paper focuses on three of the seven technologies: vertical open loop ground source heat pumps, large wind turbines and solar farms.

3.2. Multi-criteria decision analysis

The team selected a linear weighted sum model (WSM) for evaluating, scoring and ranking resource and constraints. This is a MCDA Multi-Attribute Utility Theory (MAUT) method [70] and was chosen due to its relative ease of use and its suitability for spatial problems - unlike many other MCDA methods it is site independent as it does not rely on pairwise comparisons that hugely slow down the generation of on-the-fly/live outputs.

The project team assigned utility (scores) to a range of different attributes to quantify values and/or preferences (ranked/scored outputs). The WSM was applied to calculate a score for resource and constraints

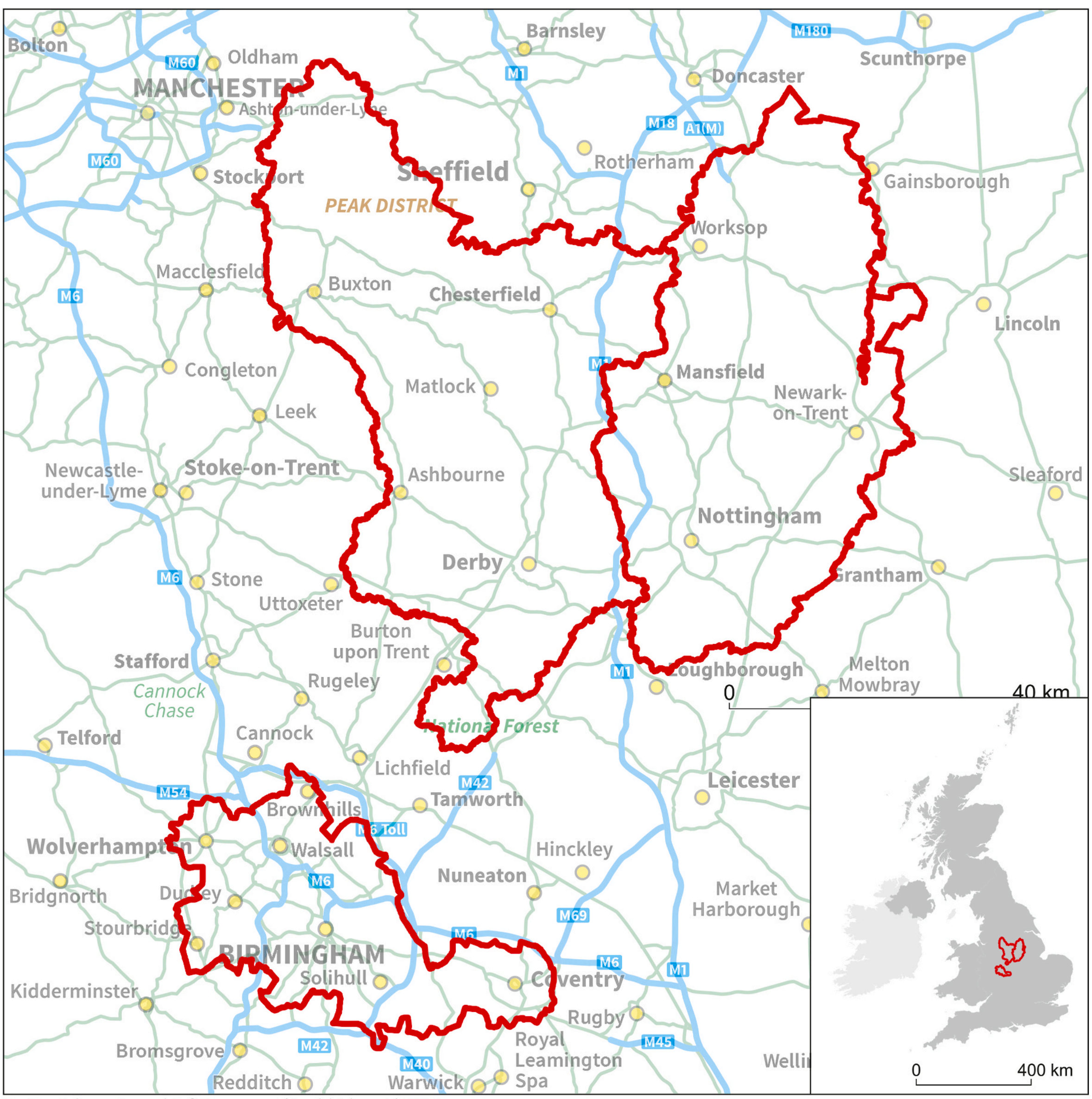

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Fig. 2. D4S study area of Derbyshire, Nottinghamshire and West Midlands, England. Contains Ordnance Survey data © Crown copyright and database right 2021.

for 10 × 10 m grid cells that make up the study area. These scores were normalised as a linear weighted sum of its scores across *n* factors. The project team assigned weightings to each criterion to each dataset/attribute. The actual scores are commercially sensitive and therefore not included in this article. The WSM score for both resource constraints is calculated by Eq. (1).

$$A_i^{WSMScore} = \sum_{j=1}^{n} w_j\, a_{ij}\ ,\ for\ i = 1, 2, 3, \cdots, m \tag{1}$$

where w_j denotes the relative weight of importance of the criterion C_j and a_{ij} is the performance value of alternative A_i when it is evaluated in terms of criterion C_j, the total (i.e., when all the criteria are considered simultaneously) importance of alternative A_i, denoted as $A_i^{W_{SM}\text{-score}}$ [71].

Despite the ease of implementation, and the ability to add or subtract an infinite number of criteria, this method is unsuitable when the criteria used are expressed in different domains e.g. feature presence/absence versus depth in metres. Where this situation existed the criteria were transformed to ranked class (e.g. 1–5) for analysis [70,72].

3.3. Generalised geoprocessing workflow

D4S is based on three separate choropleth (heat) maps for each RET: i) resource; ii) constraints; iii) feasibility map (Fig. 2). Input datasets used for the resource and constraint maps came from a number of different organisations including British Geological Survey, Natural England, Environment Agency, Ordnance Survey. Data cataloguing, quality assurance and license agreements were managed throughout the project to ensure compliance with the relevant license conditions.

The creation of the resource maps used bespoke GIS workflows created in ESRI's Model Builder™ and ArcGIS™ Version 10.1 software. Outputs were fully attributed 10 m × 10 m grid cells, including source data fields and a normalised WSM output score from 0 to 1.

Generation of the resource and constraints summary maps for each technology involved selecting and scoring <80 datasets e.g. solar radiation, protected areas, residential sites, rivers. Geoprocessing and attribution of individual grid cell was automated using an ArcGIS™ Python programme. The script iterated through each dataset performing the following operations:

1. Clip source data to study area;
2. Buffer all features in dataset using a distance defined by expert elicitation;
3. Allocate score to buffered features on a range from 0 (an exclusion where the technology should not be located) to 6 (no issues with locating technology at this site);
4. Convert dataset to a raster grid (10 m × 10 m cells);
5. Multiply each source raster grid to generate an overall constraint score for each cell; Note, that the use of one or more 0 exclusion scores for the input dataset results in an exclusion in the final output map; and
6. Normalise the scores to generate a final constraint map as a 10 m × 10 m grid of cells scored between 0 and 1.

RET feasibility maps were created by multiplying together the resource and constraint WSM scores for each cell. All three maps (resource, constraint and feasibility) were symbolised with an appropriate colour ramp using the Jenks natural breaks classification method [73] prior to publication map services, via ESRI's ArcGIS Server™ ready for integration into the Web GIS.

3.4. Detailed workflow for resource calculations

Resource estimates were made for each 10 m × 10 m grid cell using technology specific datasets in the WSM. Individual attributes were scored and Resource Scores (RS) multiplied together to provide the final score for individual grid cells. The final scores were then rescaled by dividing the score by the maximum value within the study area to give a range from 0 to 1 (Eq. (2) and Eq. (3)).

$$(\boldsymbol{Rescaled\_Resource\_Score})_{1..j} = \left(\frac{\boldsymbol{Resource\_Score\_ProductSum}_{1\ldots r}}{(\boldsymbol{Resource\_Score\_Max})_{study\ area}}\right)_{1..j} \tag{2}$$

Where r = resource layer 1 to r and for each pixel (10 m × 10 m grid cell) is 1 to j.

Where Resource_Score_ProductSum$_{1\ \ldots\ j}$ is defined by Eq. (3):

$$Resource\_Score\_ProductSum_{1\ldots r} = \sum_{1}^{r}(RS_1 \times RS_2 \times RS_3 \times \ldots RS_r) \tag{3}$$

3.4.1. Vertical open loop ground source heat pump

Vertical open loop ground source heat pump (GSHP) systems extract water from aquifers, pass it through a heat exchanger and then a heat pump. The water is then returned to the aquifer via a second borehole some distance away from the extraction borehole. Vertical open loop systems are usually accessing low grade heat stored in groundwater in geological formations where the system is located.

Vertical open loop GSHP systems rely on local hydrogeological and economic conditions including the presence of an underground water source of sufficient productivity, water quality and temperature and reasonable installation and pumping costs. It is also necessary to secure regulatory approval for both abstraction and discharge permits to protect the capacity and water quality of the aquifer.

Vertical open loop ground source heat pump resource input data for the D4S in the West Midlands comprise three publicly available BGS datasets: i) aquifer productivity; ii) depth to ground water; and iii) estimated water temperature [74] (see Table 1). Attributes in each of these datasets were ranked and given a score (Table 2) and applied to Eq. (2) and Eq. (3).

3.4.2. Large wind turbines

Large wind turbines for current UK onshore wind farms most commonly comprise of three-blades with an overall rotor diameter of 30–50 m, a tower ≥70 m tall with a generating capacity of >100 kW. Wind energy is calculated using the cube law which means a 10% increase in wind speed results in an increase of approximately 30% available energy. At locations where there are high wind speeds, the large rotors and high towers yield more energy. However, as per all locations generation capacity is subject to a range of constraints.

Environmental and/or planning constraints control onshore turbine size and wind farm layout along with access conditions for the turbine infrastructure and installation equipment. The optimal locations for

Table 1
D4S resource scoring for vertical open loop ground source heat pump.

Variable	Classification	D4S Score
Bedrock Aquifer Potential	>60 m^3/h	6
	30–60 m^3/h	5
	10–30 m^3/h	4
	<10 m^3/h	3
Depth to Groundwater	<30 m	6
	30–100 m	5
	>100–200 m	4
	>200–300 m	3
	>300–1000 m	2
	>1000 m	0
Groundwater Temperature	>25 °C	6
	15–25 °C	5
	10–15 °C	4
	6–10 °C	3
	<6 °C	2

Table 2
D4S scoring for the large wind primary resource layer.

Resource dataset	Classification	Justification	Score
Windspeed (m/s), long-term mean based on NOABL at 45 m (ETSU)	<5.0 ≥5.0–5.5 ≥5.5–6.0 ≥6.0–6.5 ≥6.5–7.0 ≥7.0–8.0 ≥8.0	Large wind power not generally viable at sites with an annual mean wind speed under 5 m/s and because the energy available is proportional to the cube of the wind speed, sites over 8.0 m/s offer a very suitable resource	0 1 2 3 4 5 6
Height (m) (NEXTMap, CEDA)	Used to scale z_o and d	Local surface roughness elements derived according to the local terrain relief (surface height taken from the NEXTMap DSM-DTM surface at 5 m resolution). Used to scale the roughness element height (z_o) and zero plane displacement (d).	Not scored, local (pixel) input value

NOTES: i) The scores in the table range between 0 and 6, where 0 is categorised as an 'exclusion' based on no expected resource and 6 is 'very high resource' expected; ii) the ETSU NOABL Windspeed database [78,79] values at 45 m were modified to estimate windspeed at an assumed hub height of 80 m by using the logarithmic wind profile equation, in which local roughness and zero plane displacement were estimated from the DSM-DTM (difference between the 5 m NEXTMap [77,80] Digital Surface Model and Digital Terrain Model). This Roughness Height Scaled model approach provides an indicator of relative wind speeds across sites only and was applied across the entire area.

wind speed are typically exposed locations which also attract higher installation and grid connection costs. These factors along with access affect the economic viability of wind farms. The development of lower wind sites near population centres increased under the now defunct Renewables Obligation [75] has since decreased. Environmental considerations, especially visual impact and designated landscapes limits the number of sites which are suitable. While the cost per installed capacity is higher for offshore wind systems, average wind speeds are higher at sea. Current constraints for onshore wind include grid capacity, finance, air defence radar, and the engineering of deeper foundations [76]. For the purposes of resource estimates and characterisation of constraints, a standard turbine has been assumed to have a tower height of 80 m and a blade diameter of 45 m so maximum height of 125 m. The height scaled resource estimates were derived using the NextMap DEM [77] to parameterise the logarithmic profile equation.

3.4.3. Solar photovoltaics

Solar photovoltaic (PV) farms, often referred to as solar parks or solar fields, are the large-scale application of solar photovoltaic panels to generate electricity. These PV farms usually feed directly into the national grid. Solar farms are typically ground mounted systems of one acre or larger and developed in rural areas, though urban solar farms are not impossible with installations in areas such as covered park and ride sites or underutilised post-industrial brownfield land. In practice there is a continuum between solar farms, and smaller patches of PV on farms and large garden installations. Solar farms go through a rigorous planning procedure before they are approved; the planning process considers the suitability of the specific site, potential adverse impacts on the area, and relevant renewable energy targets. The energy output of farms is determined by the annual irradiation and the orientation of the systems. Solar Farms are arguably the lowest impact renewable energy option, with no moving parts, no emissions while in use, little need to move large items during the installation, few vehicle movements after installation, low visible profile, and the potential for continued use of the land for grazing and wildlife, as well as a very limited impact on decommissioning. The use of poorer quality agricultural land is preferred.

The area solar radiation model in ArcGIS was used to derive incoming solar radiation based upon a user defined raster surface Digital Elevation Model (DEM). The DEM model used as the input for this tool was the 5 m resolution Digital Terrain Model data (DTM) from the NEXTMap British Digital Terrain Model project [77] and is described by Sanders et al. (2005) [80]. The parameters used to derive solar radiation are presented in Table 3. The proportion of normal radiation assumed to be diffused was set at 30% whilst the atmospheric transmissivity of radiation was assumed to be 50%. A Standard Overcast Sky diffuse model was assumed [81]. An estimate of solar radiation (kWh/m^2/day) was then scored (Table 4) and used to generate the resource maps.

3.5. Land use planning and environmental constraints

Seventy-eight spatial datasets characterising land use (e.g. pylons, aeronautical radar sites, buildings, roads), environmental (e.g. conservation sites, flood risk) and geohazards (eg compressible ground, landslides) constraints were identified and scored by the project team. Scores assigned to each dataset ranged from 1 to 6. The lowest score (1) represented a potential RET exclusion zone (e.g. roads, pylons, railways) and the highest indicating no know constraints effect on RET viability (6) (e.g. agricultural land, conservation area).

Constraints classes and scores were attributed to each 10 × 10 m grid cell. The datasets, classes and scores can not be reproduced here due their commercially sensitivity. A small sample of the data are presented in the results section. Each score is rescaled to the maximum score in the study area to give a range from 0 to 1 and then multiplied together to give a constraint viability score (CVS). The product is then rescaled again to the maximum value to give a value within the study area from 0 to 1 and mapped. For layer specified Constraint_Viability_Score 1 … i (with CVS varying between a value of 0 and 6), across cells 1 … j, the Rescaled Constraint Viability Score (varying between 0 and 1) can be defined by Eq. (3) (for constraint layer 1 to i; for each pixel 1 to j):

Table 3
Inputs and justification for the ArcGIS Area Solar Radiation tool used for generating the solar resource layer.

Input	Value/Selection	Justification
Input Raster (DEM)	5 m NextMap DTM (resampled to 10 m)	10 m based on run-time consideration (see Table 2)
Latitude (°N)	52.933	Automatically calculated mean value across DEM (extends across 1.2° latitude)
Sky size/ Resolution (cells)	200	Value sufficient for whole DEMs with large day intervals (i.e. >14 days)
Time Configuration	Whole Year	Annual statistic required (i.e. long-term values at a site)
Day Interval	Calendar month	Whole year calculation
Hour interval	Not applicable	Whole year calculation
Create outputs for each interval	No Interval	Single outputs for annual estimates
Z factor	1	x, y, z all in same units (m)
Slope and aspect input type	Derived from DEM (see above)	
Calculation Directions	32	Adequate for complex topography, minimum number likely to be acceptable for 10 m DEM resolution (increase for a DSM including man-made structures or national tool)
Zenith divisions	8	Default (low number for prototype)
Azimuth divisions	8	Default (low number for prototype)
Diffuse model type	Standard Overcast Sky	Diffuse radiation flux varies with zenith angle (i.e. valley bottoms will receive less diffuse radiation compared to ridgelines or peaks)
Diffuse proportion	0.3	Default value for generally clear sky conditions
Atmospheric Transmittivity	0.5	Default value for generally clear sky conditions

Table 4
D4S scoring for the solar primary resource layer.

Global solar radiation estimate (upper limit)			Percentage of Pixels (Study Sites)	Resource Viability Score
W/m2/yr	kWh/ m2/day	Equivalent Annual Insolation (kWh/ m2)		
<182,500	<0.5	<183	0.00002	1
<273,750	<0.75	<274	0.00007	1
<365,000	<1	<365	0.00084	2
<456,250	<1.25	<456	0.00613	2
<547,500	<1.5	<548	0.03935	3
<638,750	<1.75	<639	0.14884	3
<730,000	<2	<730	0.42478	4
<821,250	<2.25	<821	1.41778	4
<912,500	<2.5	<913	39.60970	4
<1,003,750	<2.75	<1004	56.12470	5
<1,095,000	<3	<1095	2.19808	5
<1,186,250	<3.25	<1186	0.02969	6

NOTE: UK annual insolation varies between circa 750–1100 kWh/m2.

$$(\textit{\textbf{Rescaled\_Constraint\_Viability\_Score}})_{1\ldots j} = \left(\frac{\textit{\textbf{Constraint\_Viability\_Score\_ProductSum}}_{1\ldots i}}{(\textit{\textbf{Constraint\_Viability\_Score\_Max}})_{\textit{study area}}}\right)_{1\ldots j} \tag{5}$$

The Constraint_Viability_Score_ProductSum$_{1\ \ldots\ i}$ is defined by Eq. (6):

$$\text{Constraint\_}\textit{Viability\_Score\_ProductSum}_{1\ldots i} = \sum_{1}^{i}(CVS_1 \times CVS_2 \times CVS_3 \times \ldots .CVS_i) \tag{6}$$

3.6. Feasibility data and mapping

Feasibility scores for each 10 m × 10 m grid cell were calculated as a product of the resource score and constraints scores. This product value was then rescaled using the maximum value within the study area to give a range from 0 to 1 and mapped (Eq. (5) and Fig. 5).

The Feasibility_Score for each cell 1 … j across the test area can be defined by Eq. (5):

$$(\textit{\textbf{Site\_Feasibility\_Score}})_{1\ldots j} = \left(\frac{(\textit{\textbf{Rescaled\_Constraint\_Viability\_Score}})_{1\ldots j} \times (\textit{\textbf{Rescaled\_Resource\_Score}})_{1\ldots j}}{(\textit{\textbf{Rescaled\_Feasibility\_Score\_Max}})_{\textit{study area}}}\right) \tag{7}$$

The Site_Feasibility_Score_Max is equal to the highest Eq. (5) numerator across the study area.

3.7. Web GIS visualisation and functionality

Following the creation of technology resource, constraint and feasibility maps, discussions took place with stakeholders and potential end users to determine the most effective way to visualise the data in order to facilitate the identification of opportunities for renewable energy.

This process relied heavily on the use of rapid prototyping techniques such as wireframe mock-ups to present and refine potential functionality and user interface ideas. Following a number of iterations, a design for a web-based decision support system was finalised. This application was then developed using the following technologies:

- HTML and JavaScript for the client application;
- ESRI's ArcGIS API for JavaScript for mapping components; and
- ASP. NET (Visual Basic) for server-side requests.

Functionality included publishing key outputs and map extracts into standardised preformatted PDF documents which were later emailed to the user.

4. Results and discussion

Data4Sustain (D4S) was developed as a potential solution to the 'problem statement' defined in Section 1. D4S brings together over 30 datasets in a single web-based user interface designed for rapid early-stage assessments of multiple RETs in the study area. The literature based research, also presented in Section 1, shows that there are no other tools that provide multi-technology assessments using a thorough and site focussed appraoch. D4S also provide a solution that does not require any GIS skills to use and evaluate outputs. This means it is open to a wide range of potential end-users, providing a low effort and efficient way of understanding how a large number of datasets and multi-criteria decision analysis can inform decision-making. The following sections describe three of the seven RETs to show how the problem statement has been addressed for the selected end users.

4.1. Vertical open loop ground source heat pump

An example of D4S output for vertical open loop ground source heat pumps (v-GSHP) is shown in Fig. 3. The extract shows an overall good resource potential for the entire postcode area where any installation may be constrained by water bodies, roads & buildings (red). This location was selected as it is a known installation of eight closed loop boreholes. While the area is clearly not for an open loop system, the data

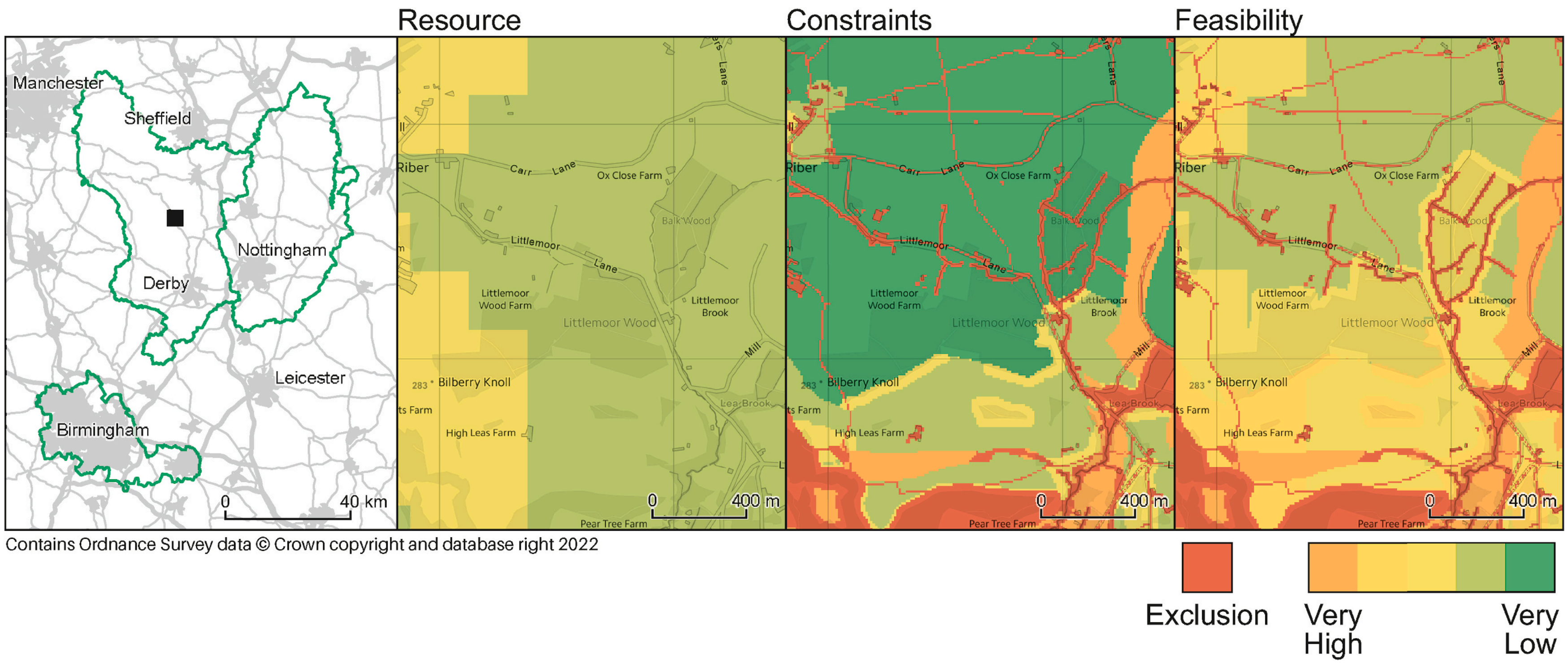

Fig. 3. Example of D4S output for vertical open-loop GSHP installation, urban fringe, Derbyshire where the heat map outputs run from red (unsuitable) to green (suitable). Contains Ordnance Survey data © Crown copyright and database right 2021.

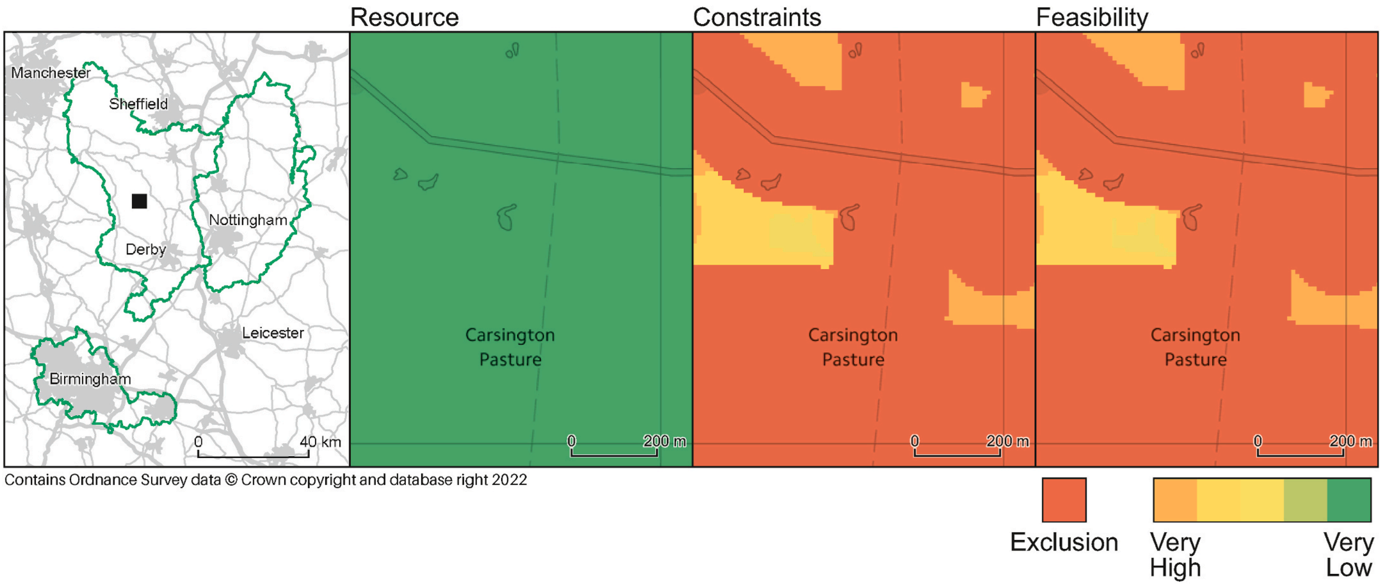

Fig. 4. Successful installation of four high power wind turbines at Carsington Pasture, Derbyshire. Contains Ordnance Survey data © Crown copyright and database right 2021.

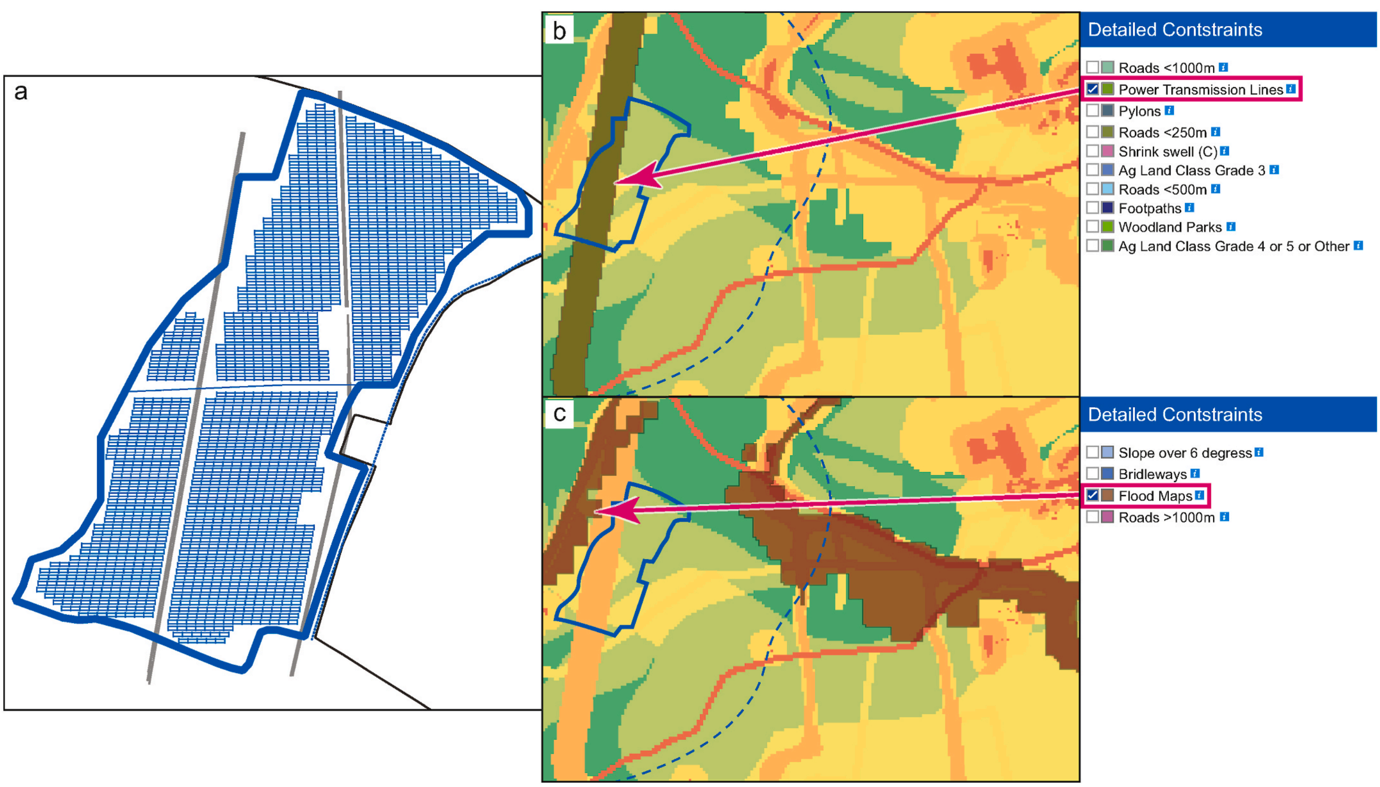

Fig. 5. Constraint Details (a: Solar panels b: Power Transmission Line c: Flood Map). Contains Ordnance Survey data © Crown copyright and database right 2021.

show comparable constraints resource, constraints and overall feasibility.

4.2. Large wind turbines

The D4S outputs for large wind turbines for a site in Derbyshire (Fig. 4) indicate excellent resource potential but the presence of soluble rocks, power transmission lines, roads, and nearby ancient monuments and heritage assets could compromise feasibility. The presence of power transmission lines (North-South) is not a constraint as they provide excellent grid connectivity [82].

The site evaluated has been subject to significant attention in the news and academic literature. While the project was successfully granted planning permission, it suffered considerable delays and cost overruns for failing to account for the karstic nature of bedrock limestone (soluble rocks constraint) [27]. D4S identified that this site might be constrained by soluble rocks, which provides an indication of its effectiveness at identifying early-stage project risks.

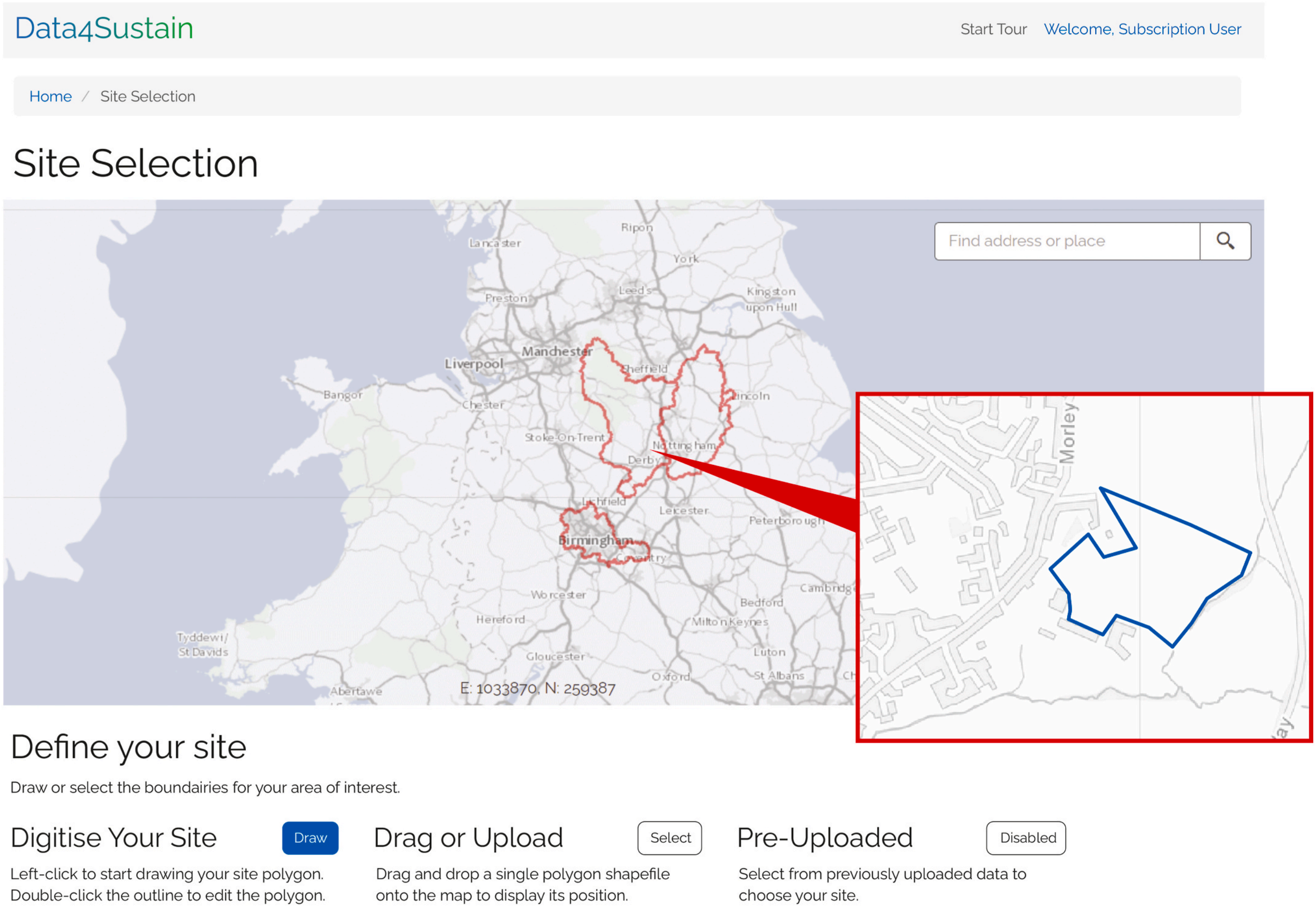

Fig. 6. D4S Web GIS Site Selection functionality. Contains Ordnance Survey data © Crown copyright and database right 2021.

4.3. Solar photovoltaics

D4S outputs for solar photovoltaics (Fig. 5) confirm excellent resource potential, however feasibility may be constrained by roads and geotechnical issues such as shrink-swell clay. The presence of power transmission lines (orange north-south feature) provides excellent grid connectivity.

The site evaluated is now a 10 MW operational solar farm [83] supporting the conclusions drawn by D4S.

Fig. 5 shows the extent of the solar panels (Fig. 5a [84]) in relation to the constraints. D4S shows that the constraint crossing the middle of the site (orange north-south feature) is actually a power line provides excellent grid connectivity (Fig. 5b). The constraint on the western boundary is flood risk (Fig. 5c) and the solar panels appear not to extend into the flood zone (Fig. 5a). The presence of the flood zone and the extent of the current solar farm layout supports D4S' ability to identify relevant features affecting site feasibility.

4.4. Web GIS and reporting

The D4S Web GIS application was developed as three modules of increasing detail, allowing users to make decisions on the appropriateness of each and all renewable technologies at a location.

4.4.1. Site selection

The site selection tool allows users to define a site of interest within the three study areas of Nottinghamshire, Derbyshire and the West Midlands (Fig. 6). The site can be defined either by digitising the site over an Ordnance Survey base map within the web browser or by uploading a polygon of a site boundary.

4.4.2. Compare Technologies

The technology comparison section provides a quick comparison of the seven technologies giving an initial indication of which technologies have the potential to be suitable at the location (Fig. 7). Colours ranging from Red (technology excluded at selected site) to Green (technology highly feasible at selected site).

For each technology, the resource, constraint and feasibility maps can be viewed individually by clicking on the tabs on the screen to identify spatial variations in the scores across the selected site.

4.4.3. Detailed technology analysis

The detailed technology analysis section (Fig. 8) allows a chosen technology to be interrogated in greater detail. The interactive map has resource, constraint and feasibility layer and include a contains a detailed constraints map. These help the user understand how each constraint might be affecting the feasibility of that technology.

In the example below the constraint of shrink swell soils may affect the foundation design but is unlikely to preclude development of the RET. By contrast, the constraint of residential buildings would be expected to prevent development of a many RETs.

The Web GIS also included functions to:

- Annotate the mapping interface allowing the user to highlight areas of interest;

Fig. 7. Data4Sustain Web GIS Compare Technologies functionality. Contains Ordnance Survey data © Crown copyright and database right 2021.

- Upload external a polygon or csv file to indicate the location of existing renewable sites to aid with groundtruthing the D4S outputs; and
- A reporting tool to generate comprehensive PDF reports delivered via email, which contained maps and information detailing the feasibility of the technology at the selected site.

In combination these techniques allow users to undertake a complete assessment and decision-making process using the power of GIS without needing specialist GIS knowledge. D4S synthesises data to meet user requirements for early-stage planning and deployment of renewables.

4.5. Opportunities for improvement

D4S is designed for early-stage and site-based evaluations of renewable energy resource, constraints (e.g. planning, physical, geological) and overall feasibility assessments. This is unlike otherDSS which tend to provide ranked outputs comparing suitability of one site over another using pairwise comparisons [22].

D4S is a prototype meaning the challenges and opportunities for improvements are proportionate to this stage of product/software development. These challenges include validating outputs with real world case studies, developing a business model that permits scalability to UK (and beyond) and enhancing functionality in line with end user need.

In the results this paper presents limited case examples of RET installations which are compared with D4S outputs. This is because data were difficult to find in spite of Government based incentives e.g. annual reporting for domestic Renewables Heat Incentive approvals by Business Energy and Industrial Strategy (BIES) [85] and Google's renewables map [86]. In each case there is a lack of detailed location-based references against which we (and others) could compare outputs. Further research and time networking with professional installers, distribution and network operators and Government would be required to secure a suitably anonymized validation dataset to each RET. It is expected that this would be a dynamic and every improving database made public to help communities understand what RETs work, where and ideally why.

The opportunity to develop D4S into a publicly available digital product remains in development and is responsive to forthcoming changes in planning and energy policy in England [6,21]. Collectively these policies cover the need for flexibility in energy planning and highlight the importance of location. Both elements complement the multi-RET site-based approach by D4S. The drive for digital planning in the Planning for the Future White paper [6] provides both incentive and mandate for further development of D4S and similar early-stage decision support systems [22].

Increased functionality of D4S is perhaps a little ambitious given that validation and business model components remain in train. However, learning points throughout the research suggest the following improvements would greatly benefit the system:

- Indicative cost estimates for RET supply and installation;
- Estimates of generation capacity for each RET;
- Grid connection potential;

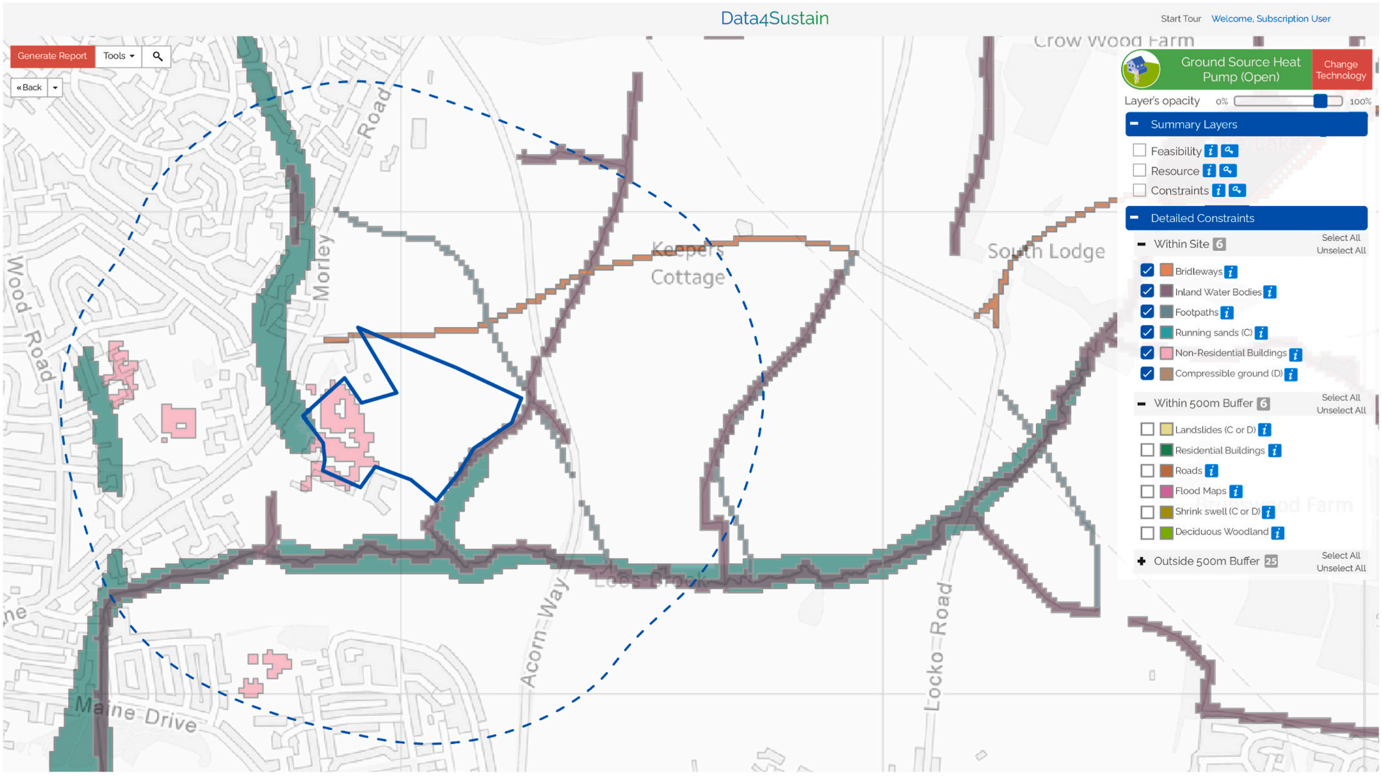

Fig. 8. Data4Sustain Web GIS Detailed Technology interrogation functionality showing constraints mapping. Contains Ordnance Survey data © Crown copyright and database right 2021.

- Spatially referenced links to relevant energy and planning policy in addition to available financial/fiscal incentives; andEarly-stage economic viability assessment based on theoretical generation capacity, installation and running costs and incentives.

None of the features highlighted in this list were detected in the literature reviewed (Section 2.4.1), meaning they would be novel and innovative approaches to both the RET and DSS literature. Each feature would be best evaluated against formal user requirements gathering and in line with new guidance on current systems thinking [87]. This will help ensure new features map to current end-user and Government need around energy and planning needs discussed in Section 2.2.

5. Conclusions

To provide people with access to energy, whilst protecting against climate change, alternatives to fossil fuels are required. Developing renewable energy sources requires evaluation of multiple factors including resource availability and constraints which could affect development or even prevent it. D4S is a practical tool to optimise the decision-making process for projects that achieve local and national policies related to generation capacity, carbon emission reductions, energy security and infrastructure resilience.

D4S has demonstrated that for the West Midlands, Derbyshire and Nottinghamshire, UK that the system can be used to quickly assess site level feasibility for seven RETs (small-medium wind, large wind, solar PV, horizontal closed loop and vertical open loop groundsource heat pumps, small hydro power and water source heat). Using the supporting data included in the system it can also be used to identify early stage project risks e.g. soluble rocks. The speed of analysis and Web GIS reporting allows non-specialists to quickly appreciate the outcomes and use them to inform decision making. D4S is scalable across the UK and elsewhere in the world, subject to information availability. Co-design of D4S by expert stakeholders ensured the biggest factors in determining resource and constraints, both political and technical, for each RET were given appropriate consideration.

As an early-stage planning decision support system, D4S provides a strong digital evidence base for the implementation and thus decarbonisation of de-centralised energy production. It is a transparent, repeatable and adaptable method that has been co-developed with sector experts to reflect factors influencing resource potential, constraints and overall feasibility. The method is at prototype stage and there is scope to tailor the method to include a range of other factors including local planning policies and new and expected guidance from the Government on energy, planning and related incentives schemes.

Credit author statement

Darren Beriro – lead author, digital lead and BGS project manager; Judith Nathanail – project manager and co-implementation of wind and solar models; Juan Salazar – energy policy review; Andrew Kingdon – drafting, reviewer and editing; Andrew Marchant – GIS lead, reviewing and editing; Steve Richardson – web GIS lead, reviewing and editing; Andy Gillet – implementation of solar and wind models; Svea Rautenberg – GIS processing and creation of figures; Ellis Hammond – review of DSSs, review and editing John Beardmore – renewables specialist and co-creation of MCDA model; Terry Moore – geospatial specialist, quality assurance of modelling; Phil Angus – renewables feasibility specialist, policy and MCDA development; Julie Waldron – energy policy review; Lucelia Rodrigues – energy policy review; Paul Nathanail – reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

[1] United Nations. Work of the statistical commission pertaining to the 2030 agenda for sustainable development. 2017.

[2] IPCC. Climate Change 2021. The physical science basis: summary for policymakers. 2021. https://doi.org/10.1260/095830507781076194. Geneva, Switzerland.

[3] IPCC. In: Pachauri RK, Meyer LA, editors. Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change [core writing team. Geneva, Switzerland: Gian-Kasper Plattner; 2014.

[4] United Nations. The Paris agreement. 2015.

[5] UK Government. Explanatory memorandum to the climate change Act 2008 (2050 target amendment) order 2019. 2019. https://www.legislation.gov.uk/ukdsi/2019/9780111187654/pdfs/ukdsiem_9780111187654_en.pdf. [Accessed 18 August 2021].

[6] UK HM Government. Energy white paper: powering our net zero future. 2020.

[7] OFGEM. Review of GB energy system operation. 2021. https://www.ofgem.gov.uk/publications/review-gb-energy-system-operation. [Accessed 27 September 2021].

[8] OFGEM. Department for business energy & industrial strategy. In: Transitioning to a net zero energy system: smart systems and flexibility plan 2021; 2021. London.

[9] Babatunde OM, Munda JL, Hamam Y. Power system flexibility: a review. Energy Rep 2020;6:101–6. https://doi.org/10.1016/J.EGYR.2019.11.048.

[10] Department for Business Energy and Industrial Strategy. British energy security strategy. 2022. https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy#networks-storage-and-flexibility. [Accessed 31 May 2022].

[11] Cajot S, Mirakyan A, Koch A, Maréchal F. Multicriteria decisions in urban energy system planning: a review. Front Energy Res 2017:10. https://doi.org/10.3389/FENRG.2017.00010.

[12] UK Statutory Instruments. The feed-in tariffs order 2012. 2012.

[13] UK Statutory Instruments. The feed-in tariffs (amendment) (No. 3) order 2015. 2015.

[14] UK Statutory Instruments. The smart Export guarantee order 2019. 2019.

[15] UK Public General Acts. Energy act 2008. 2008. https://www.legislation.gov.uk/ukpga/2008/32/section/41. [Accessed 18 August 2021].

[16] Department for Business Energy & Industrial Strategy. Contracts for difference. 2020. https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference. [Accessed 18 August 2021].

[17] Salazar J, Waldron J, Rodrigues L. Regulatory and policy framework for the uptake of renewable energy generation in the United Kingdom. In: Proc. 18th int. Conf. Sustain. Energy technol. vol. 3; 2019. p. 445–54. Kuala Lumpur, Malaysia: SET 2019.

[18] Castaneda M, Zapata S, Cherni J, Aristizabal AJ, Dyner I. The long-term effects of cautious feed-in tariff reductions on photovoltaic generation in the UK residential sector. Renew Energy 2020;155:1432–43. https://doi.org/10.1016/J.RENENE.2020.04.051.

[19] Manditereza PT, Bansal R. Renewable distributed generation: the hidden challenges – a review from the protection perspective. Renew Sustain Energy Rev 2016;58:1457–65. https://doi.org/10.1016/J.RSER.2015.12.276.

[20] UK HM Government. Planning for a sustainable future: white paper. 2007.

[21] Ministry of Housing Communities & Local Government. Planning for the future. 2020. London.

[22] Hammond EB, Coulon F, Hallett SH, Thomas R, Hardy D, Kingdon A, et al. A critical review of decision support systems for brownfield redevelopment. Sci Total Environ 2021;785:147132. https://doi.org/10.1016/j.scitotenv.2021.147132.

[23] Ministry of Housing Communities and Local Government. National planning policy framework. London: Her Majesty's Stationery Office; 2019.

[24] Ministry of Housing Communities & Local Government. Guidance: renewable and low carbon energy. 2015. https://www.gov.uk/guidance/renewable-and-low-carbon-energy#developing-a-strategy-for-renewable-and-low-carbon-energy. [Accessed 27 September 2021].

[25] Ministry of Housing Communities & Local Government. Guidance: renewable and low carbon energy. 2015. https://www.gov.uk/guidance/renewable-and-low-carbon-energy. [Accessed 24 August 2021].

[26] Guarini MR, Battisti F, Chiovitti A. A methodology for the selection of multi-criteria decision analysis methods in real estate and land management processes. Sustainability 2018;10. https://doi.org/10.3390/su10020507.

[27] Czerewko MA, Bastekin A, Tunnicliffe J, O'Rourke R. Wind turbine construction in and around Carsington Pasture in Derbyshire; overcoming the challenges posed by difficult ground conditions. Q J Eng Geol Hydrogeol 2019;52:459–80. https://doi.org/10.1144/QJEGH2018-198.

[28] UK Public General Acts. Town and country planning act 1990. 1990. https://www.legislation.gov.uk/ukpga/1990/8/contents. [Accessed 18 August 2021].

[29] UK Public General Acts. Planning act 2008. Statute Law Database 2008. https://www.legislation.gov.uk/ukpga/2008/29/contents. [Accessed 31 May 2022].

[30] Department for Energy & Climate Change.. National policy statement for renewable energy infrastructure(EN-3). 2011. London.

[31] UK Statutory Instruments. Climate change act 2008. 2008.

[32] Marttunen M, Lienert J, Belton V. Structuring problems for Multi-Criteria Decision Analysis in practice: a literature review of method combinations. Eur J Oper Res 2017;263. https://doi.org/10.1016/j.ejor.2017.04.041.

[33] Eom S. Decision support systems implementation research: review of the current state and future directions. 2001. p. 315–29. https://doi.org/10.1007/978-1-4615-1341-4_27.

[34] Sprague RH. A framework for the development of decisoin support systems. MIS Q 1980;4:1–26. https://doi.org/10.2307/248957.

[35] Giove S, Brancia A, Satterstrom F, Linkov I. Decision support systems and environment: role of MCDA. Decis. Support syst. Risk-based manag. Contam. Sites 2008:1–21. https://doi.org/10.1007/978-0-387-09722-0_3.

[36] Huang IB, Keisler J, Linkov I. Multi-criteria decision analysis in environmental sciences: ten years of applications and trends. Sci Total Environ 2011;409: 3578–94. https://doi.org/10.1016/j.scitotenv.2011.06.022.

[37] Jato-Espino D, Castillo-Lopez E, Rodriguez-Hernandez J, Canteras-Jordana JC. A review of application of multi-criteria decision making methods in construction. Autom ConStruct 2014;45:151–62. https://doi.org/10.1016/j.autcon.2014.05.013.

[38] Horigan V, De Nardi M, Simons RRL, Bertolini S, Crescio MI, Estrada-Peña A, et al. Using multi-criteria risk ranking methodology to select case studies for a generic risk assessment framework for exotic disease incursion and spread through Europe. Prev Vet Med 2018;153:47–55. https://doi.org/10.1016/j.prevetmed.2018.02.013.

[39] Konidari P, Mavrakis D. Multi-criteria evaluation of climate policy interactions, vol. 14; 2006. https://doi.org/10.1002/mcda.399.

[40] Velasquez M, Hester P. An analysis of multi-criteria decision making methods, vol. 10; 2013.

[41] Carayannis EG, Ferreira JJM, Jalali MS, Ferreira FAF. MCDA in knowledge-based economies: methodological developments and real world applications. Technol Forecast Soc Change 2018;131:1–3. https://doi.org/10.1016/J.TECHFORE.2018.01.028.

[42] Strantzali E, Aravossis K. Decision making in renewable energy investments: a review. Renew Sustain Energy Rev 2016;55:885–98. https://doi.org/10.1016/J.RSER.2015.11.021.

[43] Picchi P, van Lierop M, Geneletti D, Stremke S. Advancing the relationship between renewable energy and ecosystem services for landscape planning and design: a literature review. Ecosyst Serv 2019;35:241–59. https://doi.org/10.1016/j.ecoser.2018.12.010.

[44] Sánchez-Lozano JM, Henggeler Antunes C, García-Cascales MS, Dias LC. GIS-based photovoltaic solar farms site selection using ELECTRE-TRI: evaluating the case for Torre Pacheco, Murcia, Southeast of Spain. Renew Energy 2014;66:478–94. https://doi.org/10.1016/j.renene.2013.12.038.

[45] Pınarbaşı K, Galparsoro I, Depellegrin D, Bald J, Pérez-Morán G, Borja Á. A modelling approach for offshore wind farm feasibility with respect to ecosystem-based marine spatial planning. Sci Total Environ 2019;667:306–17. https://doi.org/10.1016/j.scitotenv.2019.02.268.

[46] Acheilas I, Hooimeijer F, Ersoy A. A decision support tool for implementing district heating in existing cities, focusing on using a geothermal source. Energies 2020;13. https://doi.org/10.3390/en13112750.

[47] Mwanza M, Ulgen K. Sustainable electricity generation fuel mix analysis using an integration of multicriteria decision-making and system dynamic approach. Int J Energy Res 2020;44:9560–85. https://doi.org/10.1002/er.5216.

[48] Bracco S, Delfino F, Ferro G, Pagnini L, Robba M, Rossi M. Energy planning of sustainable districts: towards the exploitation of small size intermittent renewables in urban areas. Appl Energy 2018;228:2288–97. https://doi.org/10.1016/j.apenergy.2018.07.074.

[49] Sun Y-W, Hof A, Wang R, Liu J, Lin Y-J, Yang D-W. GIS-based approach for potential analysis of solar PV generation at the regional scale: a case study of Fujian Province. Energy Pol 2013;58:248–59. https://doi.org/10.1016/j.enpol.2013.03.002.

[50] Huld T, Moner-Girona M, Kriston A. Geospatial analysis of photovoltaic mini-grid system performance. Energies 2017;10. https://doi.org/10.3390/en10020218.

[51] Aydin NY, Kentel E, Duzgun S. GIS-based environmental assessment of wind energy systems for spatial planning: a case study from Western Turkey. Renew Sustain Energy Rev 2010;14:364–73. https://doi.org/10.1016/j.rser.2009.07.023.
[52] Simão A, Densham PJ, Muki, Haklay M. Web-based GIS for collaborative planning and public participation: an application to the strategic planning of wind farm sites. J Environ Manag 2009;90:2027–40. https://doi.org/10.1016/j.jenvman.2007.08.032.
[53] Mekonnen AD, Gorsevski PV. A web-based participatory GIS (PGIS) for offshore wind farm suitability within Lake Erie, Ohio. Renew Sustain Energy Rev 2015;41:162–77. https://doi.org/10.1016/j.rser.2014.08.030.
[54] González A, Connell P. Developing a renewable energy planning decision-support tool: stakeholder input guiding strategic decisions. Appl Energy 2022;312. https://doi.org/10.1016/j.apenergy.2022.118782.
[55] Goe M, Gaustad G, Tomaszewski B. System tradeoffs in siting a solar photovoltaic material recovery infrastructure. J Environ Manag 2015;160:154–66. https://doi.org/10.1016/j.jenvman.2015.05.038.
[56] Bączkiewicz A, Kizielewicz B, Shekhovtsov A, Yelmikheiev M, Kozlov V, Sałabun W. Comparative analysis of solar panels with determination of local significance levels of criteria using the mcdm methods resistant to the rank reversal phenomenon. Energies 2021:14. https://doi.org/10.3390/en14185727.
[57] Sedrati M, Maanan M, Rhinane H. PV POWER PLANTS SITES SELECTION USING GIS-FAHP BASED APPROACH in NORTH-WESTERN Morocco. Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. - ISPRS Arch. 2019;42:385–92. https://doi.org/10.5194/isprs-archives-XLII-4-W19-385-2019.
[58] Iyappan L, Pandian PK. Geoprocessing model for identifying potential wind farm locations. IET Renew Power Gener 2016;10:1287–97. https://doi.org/10.1049/iet-rpg.2015.0187.
[59] Guler D, Charisoulis G, Buttenfield BP, Yomralioglu T. Suitability modeling and sensitivity analysis for biomass energy facilities in Turkey. Clean Technol Environ Policy 2021;23:2183–99. https://doi.org/10.1007/s10098-021-02126-8.
[60] US EPA. RE-powering mapper 2.0. 2021. https://geopub.epa.gov/repoweringApp/. [Accessed 18 August 2021].
[61] World Bank Group. Global wind atlas. 2022. https://globalwindatlas.info/. [Accessed 31 May 2022].
[62] World Bank Group. Global solar atlas. 2022. https://globalsolaratlas.info/map?c=11.609193,8.4375,3. [Accessed 31 May 2022].
[63] IntelStor LLC. Intelstor - renewable energy market research. 2022. https://www.intelstor.com/. [Accessed 31 May 2022].
[64] Solargis. Solar resource maps. 2022. https://solargis.com/maps-and-gis-data/overview. [Accessed 31 May 2022].
[65] QuickScan. QUICKScan 2022. https://www.quickscan.pro/. [Accessed 31 May 2022].
[66] Google. Project sunroof. 2022. https://sunroof.withgoogle.com/building/37.476876/-122.253535/#?f=buy. [Accessed 31 May 2022].
[67] Valentin Software GmbH. PV*SOL online. 2022. http://pvsol-online.valentin-software.com/#/. [Accessed 31 May 2022].
[68] UK Public General Acts. Planning and compulsory purchase act 2004. 2004.
[69] UK Statutory Instruments. The domestic renewable heat incentive scheme regulations 2014. 2014.
[70] Fishburn PC. Additive utilities with finite sets: applications in the management sciences. Nav Res Logist Q 1967;14:1–13. https://doi.org/10.1002/nav.3800140102.
[71] Nathanail J, Marchant A, Beriro D, Kingdon A, Richardson S, Beardmore J, et al. Using multi-criteria decision analysis to evaluate the feasibility of Renewable Energy Technologies and Sites - the Data4Sustain Web GIS decision support tool. In: GISRUK 2017 25th GIS res. UK conf; 2017. Manchester, UK.
[72] Keeney R, Raiffa H, Rajala D. Decisions with multiple objectives: preferences and value trade-offs. Syst Man Cybern IEEE Trans 1979;9:403. https://doi.org/10.1109/TSMC.1979.4310245.
[73] Jenks GF. The data model concept in statistical mapping. Int Yearb Cartogr 1967;7:186–90.
[74] Abesser C, Lewis MA, Marchant AP, Hulbert AG. Mapping suitability for open-loop ground source heat pump systems: a screening tool for England and Wales, UK. Q J Eng Geol Hydrogeol 2014;47:373–80. https://doi.org/10.1144/QJEGH2014-050.
[75] Department of Energy & Climate Change. The renewables obligation for 2016/17. 2016.
[76] Institution of Civil Engineers. Wind Energy 2014. https://www.ice.org.uk/knowledge-and-resources/briefing-sheet/wind-energy. [Accessed 18 August 2021].
[77] Intermap Technologies. NEXTMap 2009 annual report. Calgary: Canada; 2010.
[78] Department for Business Enterprise & Regulatory Reform. Windspeed database. 1996. https://webarchive.nationalarchives.gov.uk/ukgwa/20090609065721/http://www.berr.gov.uk/whatwedo/energy/sources/renewables/explained/wind/windspeed-database/page27708.html. [Accessed 27 September 2021].
[79] RenSMART. NOABL model. 2008. https://www.rensmart.com/Information/NOABLModel. [Accessed 27 September 2021].
[80] Sanders R, Shaw F, Mackay H, Galy H, Foote M. National flood modelling for insurance purposes: using IFSAR for flood risk estimation in Europe. Hydrol Earth Syst Sci 2005;9:449–56.
[81] Kennelly PJ, Stewart AJ. General sky models for illuminating terrains28; 2013. p. 383–406. https://doi.org/10.1080/13658816.2013.848985. Http://DxDoiOrg/101080/136588162013848985.
[82] The Wind Power. Wind farms- carsington pasture (United Kingdom). 2021. https://www.thewindpower.net/windfarm_en_18691_carsington-pasture.php. [Accessed 18 August 2021].
[83] Department for Business Energy & Industrial Strategy. Renewable energy planning database: quarterly extract - GOV.UK. 2021. https://www.gov.uk/government/publications/renewable-energy-planning-database-monthly-extract. [Accessed 18 August 2021].
[84] Share Offer 2015 Nottingham community energy. 2015. Nottingham.
[85] OFGEM. Distributed generation [Online]. 2020. https://www.ofgem.gov.uk/electricity/distribution-networks/connections-and-competition/distributed-generation.
[86] Google. UK renewables map. 2021. https://www.google.com/maps/d/viewer?mid=17FaYeZBcIizFSJst9CMBfpzFYUGXNpMG&ll=54.279016369147776%2C-1.1675148504181898&z=9. [Accessed 27 September 2021].
[87] Government Office for Science. Systems thinking for civil servents. 2021. https://www.gov.uk/government/publications/systems-thinking-for-civil-servants. [Accessed 31 May 2022].