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Correlating Site-Specific Meteorological Data and Power Availability for Small-Scale, Multi-Source Renewable Energy Systems

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***Abstract*—**The paper presents a modelling methodology for small scale multi-source renewable energy systems. Using historical site-specific weather data, the relationships of *cost*, *availability* and *energy form* are visualised as a function of the sizing of photovoltaic arrays, wind turbines, and battery capacity. The specific dependency of each site on its own particular weather patterns show that unique solutions exist for each site. It is shown that in certain cases the capital component cost can be halved if the desired theoretical demand availability is reduced from 100% to 99%.

***Keywords*—**Energy Analysis, Forecasting, Distributed power generation.

I. Introduction

TODAY'S energy situation requires the introduction of new generation methods. A potential new source is distributed generation of electricity from many relatively small and variable sources, harnessing local renewable forms of energy. Whilst centralised electricity generation systems tend to suggest favourable economics due to their scale, distributed generation systems can demonstrate higher efficiency through direct use of heat, lower transmission losses, and increased security and redundancy.

Such distributed systems will comprise of plant at many sites utilising multiple sources of renewable energy. These pose a number of challenges to planners, designers and users alike, in particular if the plant is to operate for significant periods of time without an operational grid connection. In this case, performance will be a function of varying sources, load demands, and the ability to store energy. In addition, it is difficult to determine, in advance, the optimum relative proportions of, for example, photovoltaic generation capacity, wind generation capacity and battery capacity, for a given site (weather pattern) and required power availability.

Much literature exists recognising the importance of the optimisation of remote renewable energy sites; generally split into three areas, sizing, control and both. Significant work includes [1-5], offering a comprehensive analysis of system components. What is not included in any of the above references is the use of real hourly data (as opposed to average or statistical representations), the inclusion of more than three years data and the inclusion in the results that allow alternative solutions depending upon reliability, cost and site make-up. It is also believed that the incorporation of a modular approach so that alternative components and control techniques can be compared would be of great use. The distribution of loss of power and the potential to drastically reduce economic cost by a degree of load control should also be considered.

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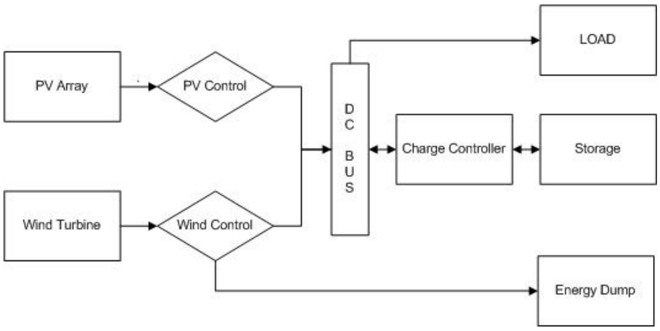

Fig. 1 Multi-Source Renewable Energy System

This paper presents a modelling method to aid in the design and evaluation of multi-source power systems. For site-specific weather data and load requirements, it visualises the trade-off between economic *cost availability* and *energy form* (the relative proportions of wind and solar, for example). In this manner, given the particular needs, a designer can arrive at the most suitable balance for preferred system architecture.

As an example to illustrate the method developed, an autonomous site powered from several renewable sources has been analysed, Fig. 1. This offers the ideal semantics through which it is possible to illustrate the principles, scales and limitations to which we must work if we are to achieve sustainable energy solutions [6].

II. A Multi-Source Site Design Method

It is important that a design method takes into account the characteristics of the technology elements, the interfaces and the control methods, as these will all affect the performance of different architectures.

Matlab and Simulink have been used to predict the renewable energy available to the power generation system, as a function of meteorological data. The model also incorporates the electrical detail needed to convert this into power successfully delivered to the load, for example a battery model adapted from [7], photovoltaic modes using [8] and wind turbine models using elements from [9].

Where possible, a modular approach has been used and this will allow the adaptation, flexibility and potential that can compare different technologies, configurations and techniques.

A. Design Method

The system as a whole can be thought of initially as a black box, whose inputs are primarily current weather conditions, requested demand and battery state of charge. The output is ultimately a Boolean value representing whether demand was met for that hour or not.

B. Using Weather Data, Characterisation and Forecast

The most common sources of distributed renewable generation are likely to include solar and wind. The variation in the likely availability of each will vary from site to site across the globe. There is considerable literature [10, 11] regarding how best to characterise this, from the creation of a general year to the use of the entire data set available. The use of hourly data values itself gives rise to certain concerns about the accuracy of ensuing model outputs [12]. There is also another area regarding site specific short term (minimum of 1 year) weather data collection and how best to correlate these with existing longer term data sets in close geographical proximity.

For the results illustrated in this paper, the MET offices MIDAS data set [13] has been used for the year 2007, thus effectively assuming the autonomous multi-source renewable energy site is located at the weather station. Details of the four sites used in this paper can be found in Table I.

TABLE I
SITE INFORMATION FOR THE WEATHER STATIONS USED

Site #	*Site Name*	*Area*	*Latitude*	*Longitude*
440	*Wattisham*	*Suffolk*	*52.123*	*0.961*
554	*Sutton Bonington*	*Nottighamshire*	*52.836*	*-1.25*
583	*Wittering*	*Cambridgeshire*	*52.611*	*-0.459*
676	*Filton*	*Avon*	*51.521*	*-2.576*

Despite all sites being in the Midlands and South, significant differences exist. Sites 583 & 440 are in rural situations towards the east coast and experience a good solar resource with site 583 also being the windiest. Site 554 is right in the centre of the country with more constant but lower levels of both wind and sun. Finally site 676 is the most variable site, being situated in an urban location near to the Seven Estuary.

C. Modelling Framework

The various model elements need to run concurrently with each other with a number of inter-dependents between various inputs and outputs of each module [3, 9, 10, 14, 15]. The modular nature of the model allows the calibration of different modules, and relative assessment of different technologies, control strategies and system architectures.

A schematic of the computer model is illustrated in Fig. 2. The model is run for a year with a time step of one hour. The observed output variable is the number of hours where demand cannot be met. The demand is no longer met as soon as the battery's state of charge falls below the defined minimum (20%), a limit used in real systems in order to prevent accelerated decay of the battery. At this point the battery is disconnected until generation once again exceeds the requested load.

For each site, an indication of the ability of each system configuration to meet the demand for each hour of the test year at that location can be found. A number of permutations representing various photovoltaic module areas, rated wind turbine powers and battery capacities are simulated with that site's weather data set – thus creating an array of configurations. The number of hours where the demand has failed to be met is represented either as a percentage of the total number of hours in that data set to provide the "% down-time", or alternatively in the form of "% availability", with 0% down-time and 100% availability being equal and the ideal targets.

D. Technology Elements

The key technology elements used in the system need to be modelled to reflect their key characteristics. The system model includes:

i) A pitching and furling variable speed wind turbine model [9] currently based on a generic power curve that starts generating at a wind speed of 2.5 knots/s and reaches and maintains the rated power of the turbine at 12 knots/s and above.

ii) The photovoltaic model [16] is based on the diode equation. Modules of $2m^2$ are modelled with 10% efficiency assumed. The equation dictates that for any given level of sunlight at a constant temperature, there is a particular voltage and corresponding current that leads to maximum electrical generation. This point is found by a maximum power point tracker, using a hill-climbing algorithm based on [8]. In reality this is a step-down power converter that is able to vary the voltage from one side of it to another, enabling it to operate the generation source at its highest potential while ensuring the output voltage is as desired.

iii) A stateflow battery controller that disconnects the battery if the state of charge is below 20% and returns a 'failed to meet demand' output [17] for that hour. It also dissipates excess energy (in practice via resistive dump loads) if the state of charge exceeds 95%, thus protecting the battery.

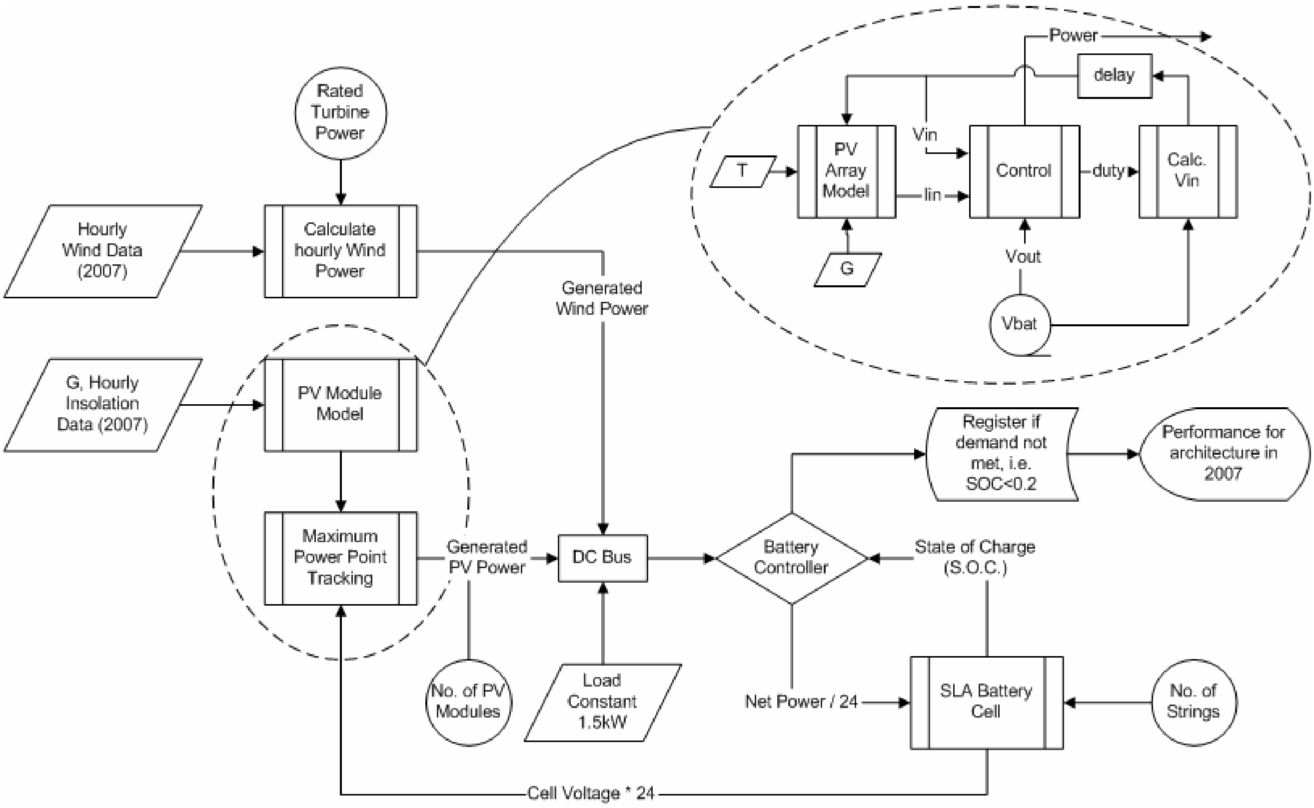

Fig. 2 Top-level schematic of Simulink model, with a further level of detail illustrated for the Photovoltaic (PV) and Maximum Power Point Tracking modules

iv) A sealed lead acid battery model adapted from [7] that represents an empirical relationship of the chemistry within the system, relating 'Voltage' and 'State of Charge' to the integral of the battery current over time since the last state of full charge. The battery is an important restraint of the autonomous system. It offers the only method to smooth the differences between the generation and demand profiles. It is common to have to replace the batteries every five years thus having a major impact on system economics. The modular approach allows, with minimum alterations, the replacement of lead acid

battery models with those representing lithium-ion, flow batteries, pump storage, flywheels or any combination. The 48V battery module consists of multiple strings each with 24, 2V, 325Ah cells. This is economically, and environmentally, an expensive item.

v) The load used for the present work has been kept constant at 1.5kW. For certain applications, for example an office or domestic household, a variable load demand with time of day and season can be incorporated. Furthermore, non-specific time demands should be considered separately and in a sense fall more under the storage category.

E. Control

There are several control techniques that can be developed to potentially improve the efficiency of any particular system or component. In the system above, a control system has been illustrated by way of maximum power point tracking with respect to the photo-voltaic generation (Fig. 2). Through modelling and prototyping, characterisation of their effect can be evaluated using the model so that the relative benefit in various situations can be assessed.

F. Optimising Cost, and other Economic Considerations

The system architecture is varied by adjusting the photovoltaic, wind and battery capacities, to explore the effect on 'ability to meet demand' across a number of different UK sites and estimated system cost. A number of techniques exist for the analysis of similar problems [3, 4, 18, 19], but do not necessarily incorporate key commercial criteria.

Here, each completed model that seeks to characterise the technical behaviour and operation of alternative technologies can also be assigned economic data. Ultimately capital, installation, operational and maintenance costs can be developed and correlated with weather. In the examples presented here an economical cost has been attributed to each architecture permutation based on estimated current capital component costs. This is calculated using a 25-year life for both the photo-voltaic panels and the wind turbines, while assuming the batteries will be replaced every five years. This allows the visualisation of which architectures offer the best value for each site and which parts of the load availability curve cost the most.

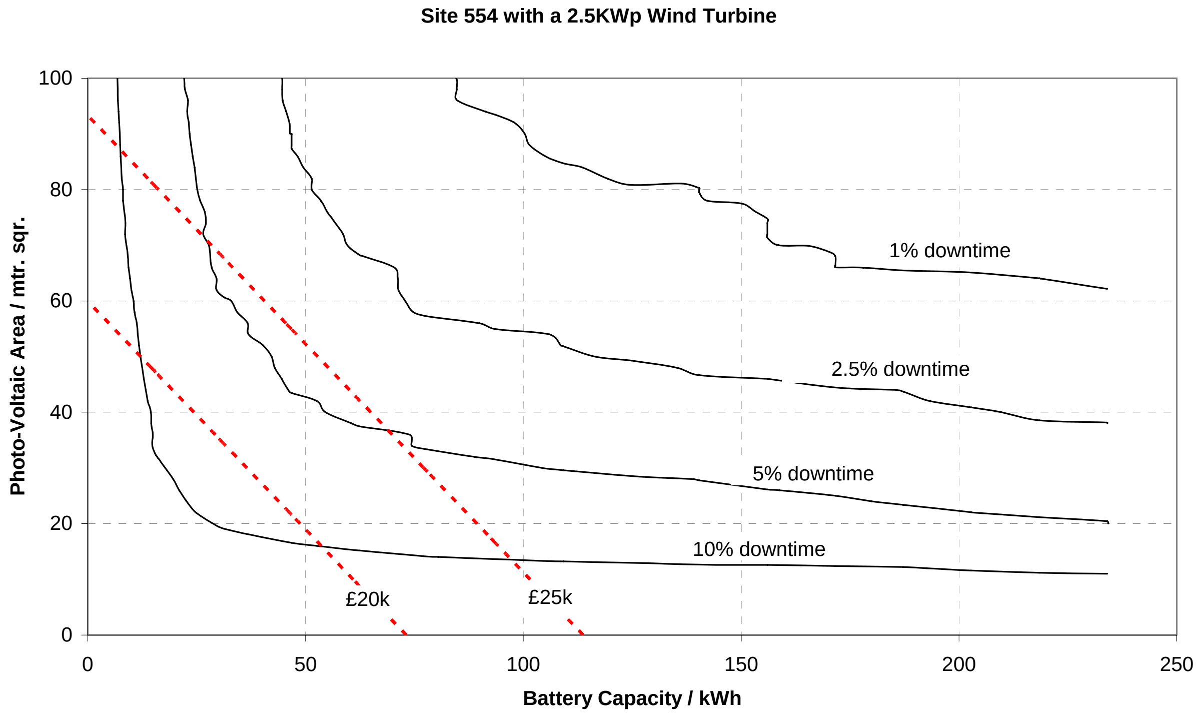

Fig. 3 The maximum system downtime (solid lines) when supply does not meet demand as a function of installed photovoltaic area and battery capacity at site 554 for systems with a peak installed wind capacity of 2.5kWp (kW peak). Lines of constant component costs (photovoltaic array, wind generator and batteries) are indicated (dashed lines)

III. Theoretical Results

Results have been calculated for eleven sites across the UK. In all, 6 dimensions are included (Solar, Wind & Battery Size, Location, Cost & Load Availability). The figures in this section show variation in one or two dimensions to illustrate a particular trade-off example. Table II illustrates the ranges for which simulations were run.

Table III shows the average (avg.) and standard deviation (std.) for the weather parameters used for each site.

TABLE II
Generation And Storage Capacities Used For Simulation

Variable	Minimum	Maximum	Resolution
Photovoltaic	0 m^2	100 m^2	2m^2
Wind Turbine	0kWpeak	10kWpeak	Discreet Values
Battery Capacity	15.6kWh	249.6kWh	15.6kWh

TABLE III
Weather Parameter Statistics

Site	Wind (avg.) Knots/s	Wind (std.)	Insolation (avg.) W/m^2	Insolation (std.)
440	9.19	4.82	436	694
554	6.90	4.08	408	656
583	9.78	5.22	430	680
676	8.25	5.49	433	709

A. Component Cost & Availability for a Site

Energy storage is relatively expensive and incurs heavy operational costs. By increasing the installed capacity to generate power, the batteries are more likely to be fully charged at the beginning of a period of low generation, and therefore battery requirement is minimised.

Fig. 3 illustrates the trade-off between installed photovoltaic capacity and installed battery storage for a typical site with moderate to low wind. For example, given the weather at site 554, a system comprising of a 45m^2 photovoltaic array and a 2.5kWpeak wind turbine would require 50kWh of storage in order to achieve a 95% availability (5% down-time). The cost lines indicate that the component capital costs (photovoltaic array, wind generator and batteries) of this system is approximately £23,000. Fig. 3 shows that it is more effective to increase the photovoltaic array and to eliminate some of the underutilised storage capacity. The system cost can be reduced by allowing a relatively small reduction in availability. Due to the small turbine installed, a high dependence upon the daily solar cycle is apparent; the site with a 45m^2 photovoltaic array would require a four-fold increase in battery capacity in order to halve the down-time from 5% to 2.5%, the cost lines show that it is more effective to double the area of the photovoltaic array, if more reliable electrification is required.

Here, the cost lines assume a 5-year battery replacement cycle. In reality, with an increase in generation capacity, the

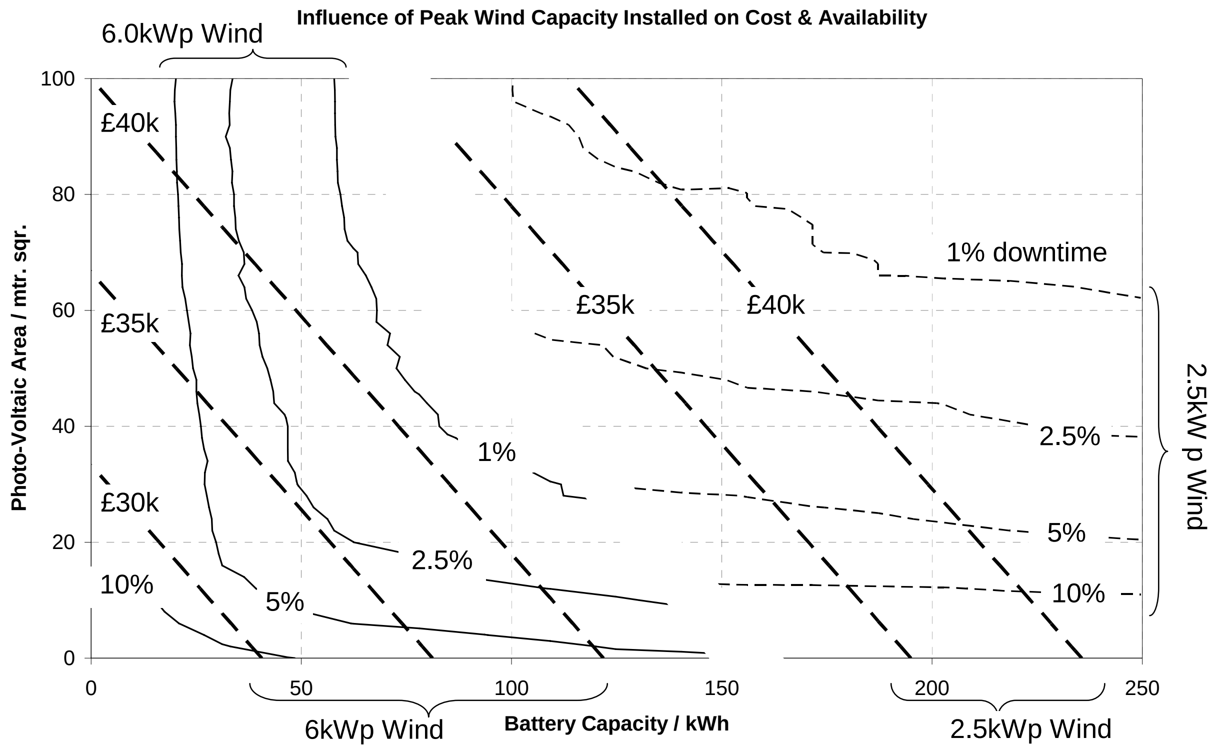

Fig. 4 System downtime as a function of installed photovoltaic area and battery capacity at site 554 for two systems: 6kWp installed wind capacity (left, solid plots) and 2.5kWp (right, dashed plots). Lines of constant component costs are indicated (dashed straight lines) for both systems

batteries experience fewer charge-discharge cycles per year and therefore last longer; more accurate cost lines would be curved and would be a function of the site.

B. Effect of Turbine Size on Cost & Availability

Increasing wind generation capacity displaces photovoltaic generation capacity and changes the storage requirements. Both of these trade-offs depend on the prevailing weather conditions.

Fig. 4 has been split, showing the results using a 6kW (peak output) wind turbine to the bottom left and a 2.5kW turbine to the right. Again cost indication lines have been added to each. For this site, a smaller wind capacity provides a more cost-effective solution due to low winds. A 1% downtime target could be achieved with a 2.5kWp turbine, 84m^2 of photo-voltaic cells and a 130kWh battery for £40k. With the 6kWp turbine a 1% downtime costs approximately £42k. However using a larger turbine enables a lower percentage downtime to be achieved if sufficient battery capacity is installed.

C. Effect of Different Sites on the Design of a Power System

Different sites favour different relative proportions of wind and solar power generation. This is illustrated in Fig. 5 with plots of the different possible generation combinations required in order to achieve 99% availability (1% downtime) for two different sites; site 554, as used in Fig. 3, and a new windier site 583.

The most obvious observation from Fig. 5 is that the windier site 583 could reach a 1% downtime level using only wind with the storage options considered, where as site 554 could not. It also shows neither site would benefit from the largest 10kWp turbine for different reasons. Site 583 meets the requirements with a 6kWp turbine. While at site 554 very little benefit is gained with 10kWp wind as opposed to 6kWp, certainly not enough to justify the £15k extra cost. This essentially indicates that there are not significant occurrences of periods of high wind where the extra generation capacity can be utilised with the proposed storage.

Fig. 5 also contains results for an increase in storage capacity; this has a larger impact for site 554, again suggesting that overall generation potential is more sporadic than site 583. In other words, site 583 appears to have a fairly steady, constant wind profile removing the need for storing energy over many days.

D. Availability Cost Curves for Different Sites

The previous sections demonstrate that for a given site there is an optimum combination of wind generation, photovoltaic generation and battery capacity, in order to achieve the required availability at minimum cost.

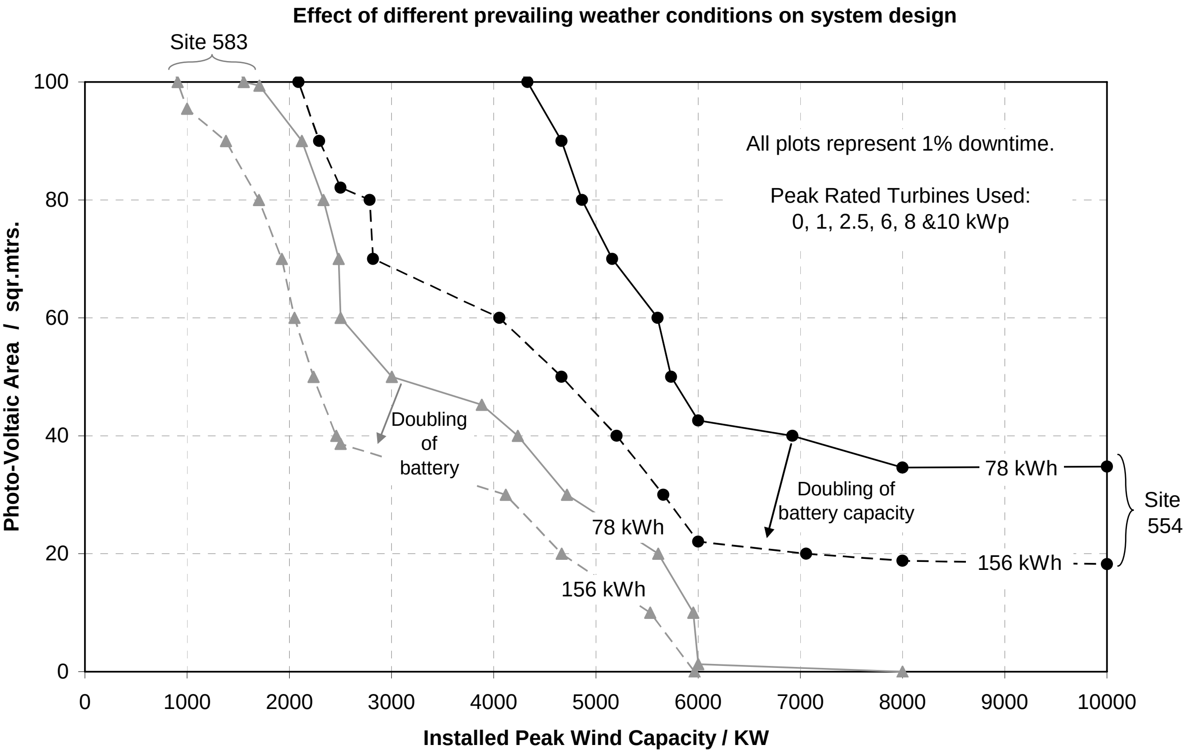

Fig. 5 How a reduction in battery capacity affects different sites (1% availability)

Fig. 6 shows the estimated capital cost against 'availability of demand' for four UK sites. A theoretical 100% availability is seen to be achieved for some sites. If an availability of 99% is acceptable, system costs can be significantly reduced, for some sites by over 50%. 99% availability here means that the system is off line for 1% of the hours in a year. Such an analysis can be of particular use when considering grid-tied systems or in situations where a diesel generator can be called upon, where a reduction in self-sufficient availability is far more viable.

The model runs in this paper have used discrete component values, in particular wind turbines. For Fig. 6, wind turbine values of 0, 0.5, 1, 2.5, 6 and 10kWhp have been used to represent readily available, off the shelf proven technologies. This may partly explain some of the stepping as seen in Fig. 6. However it is also indicative of this type of analysis, especially when the margins become very fine, nearing 100%. A particular architecture set-up can match the weather pattern and return very good value for a particular level of availability; to better this, a much more costly solution is required. It should be noted that only a single year of weather data has been used in the results published here, so while representative of results that may be expected, economical decisions based on results such as those in Fig. 6 should ideally use ten years of consistent site-specific weather data [20, 21].

IV. Conclusion

A methodology for assessing autonomous, multi-source renewable energy generation sites has been introduced. The method incorporates site specific weather variability, through which it is possible to gain and illustrate an understanding of numerous design trade-offs that vary depending upon site specific conditions and user requirements. This allows the optimal site architecture to become apparent and thus offers the customer various options with a meaningful appreciation of the relative advantages and their associated costs.

The following conclusions were drawn for the modelling method and its application:

- the optimum solution for any multi-source renewable energy station is unique depending upon location and thus local weather patterns;
- accepting a 1% downtime versus requiring 100% availability could potentially allow savings of over 50%. Whilst in some UK industries this may seem unacceptable today, many electrification projects around the world including the UK require an evaluation of costs versus availability, especially those where a grid connection is possible;
- a significant simplification used here is the assumption of a constant electric load. A daily or seasonal load variation, or a variation in feed-in tariffs, would increase the dependency of the design on the specific site chosen. Ideally, a model would include a mini-grid consisting of the specific site's loads and generators with a single grid connection that can either draw or deliver power;

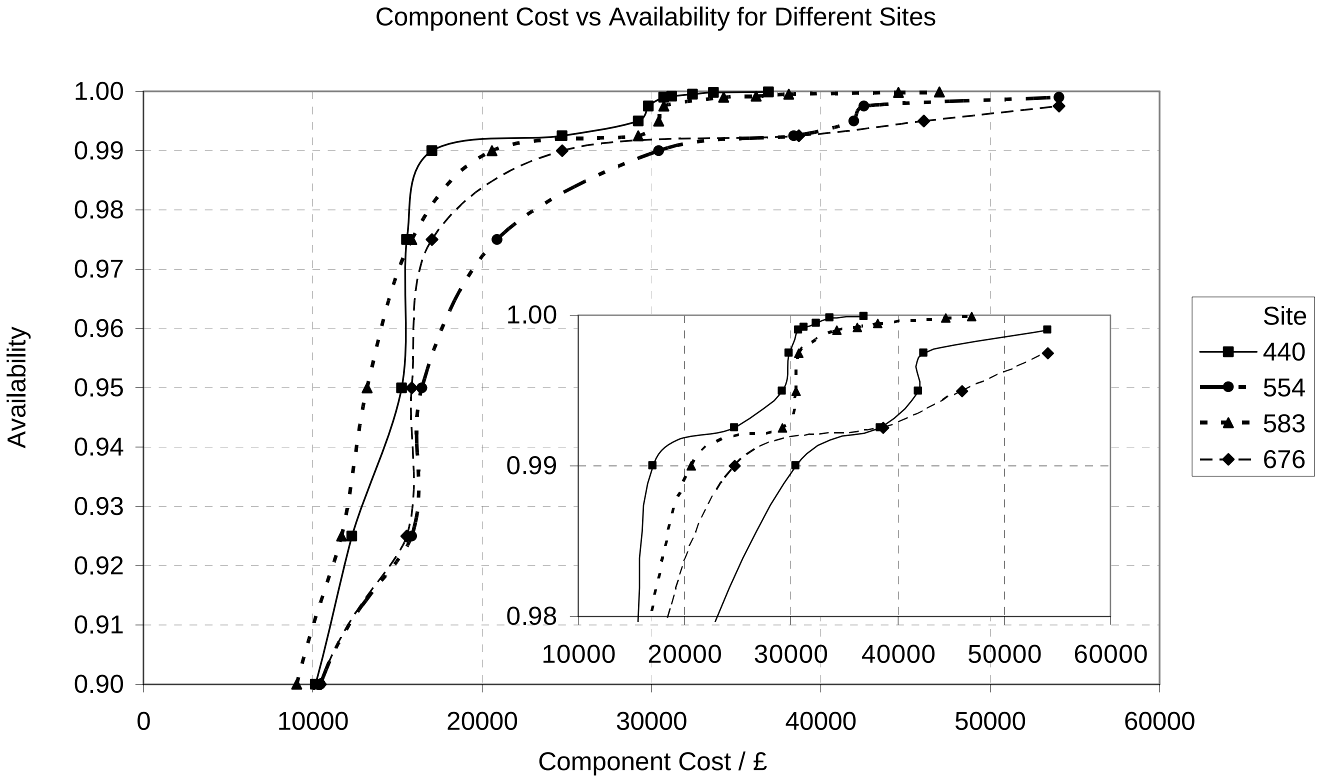

Fig. 6 The optimum cost solution for theoretical availability between 90 and 100% for four sites based on 2007 recorded weather data sets

- time stepping in hourly increments results in a lack of resolution when assessing availabilities over 99.9%;
- using availability or downtime as defined here (% of hours per year) may not be sufficient to define the quality of the power supply. There is no distinction made between consecutive hours of downtime or evenly distributed hours throughout the year. The specification could, therefore, be more complex and include a measure of the availability profile, such as '% hours per day', '% hours per month', or 'maximum number of consecutive hours down time'.

It would be beneficial if an environmental profile could be developed for each model item so that 'carbon' payback periods could be calculated in a similar manner to the economic payback periods. These could then be compared with alternatives to distributed renewable energy generation so that it is understood that fossil fuel generation, for example, never attains carbon neutrality, always making progress away from it.

The presented methods can be used to quantitatively assess different technologies and control regimes. A modular approach is important in order to facilitate collaboration, so that a wide range of technology and design alternatives can be assessed, thus leading us towards optimal sustainable power solutions.

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