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Comparative impacts of wind and photovoltaic generation on energy storage for small islanded electricity systems

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A R T I C L E I N F O

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A B S T R A C T

This paper addresses the annual energy storage requirements of small islanded electricity systems with wind and photovoltaic (PV) generation, using hourly demand and resource data for a range of locations in New Zealand. Normalised storage capacities with respect to annual demand for six locations with winter-peaking demand profiles were lower for wind generation than for PV generation, with an average PV:wind storage ratio of 1.768:1. For two summer-peaking demand profiles, normalised storage capacities were lower for PV generation, with storage ratios of 0.613:1 and 0.455:1. When the sensitivity of storage was modelled for winter-peaking demand profiles, average storage ratios were reduced. Hybrid wind/PV systems had lower storage capacity requirements than for wind generation alone for two locations. Peak power for storage charging was generally greater with PV generation than with wind generation, and peak charging power increased for the hybrid systems. The results are compared with those for country-scale electricity systems, and measures for minimising storage capacity are discussed. It is proposed that modelling of storage capacity requirements should be included in the design process at the earliest possible stage, and that new policy settings may be required to facilitate a transition to energy storage in fully renewable electricity systems.

1. Introduction

Energy storage is a key element in balancing supply and demand within islanded electricity systems, especially when variable resources such as wind and solar are used for generation. Time frames for balancing may range from minutes to seasons. Where maximum long-term utilisation of generated energy, or minimal curtailment, is an objective, then seasonal storage is of particular interest. If supply and demand are highly correlated, seasonal storage requirements will be minimised. This may occur, for example, at a location employing solar photovoltaic (PV) generation, and where annual electricity demand peaks during the summertime, due to the widespread use of air conditioning. Conversely, where supply and demand are weakly correlated, required storage capacity will be greatest.

Previous researchers have addressed the increased requirement for energy storage as the penetration of variable renewable generation increases [1–5], storage design, including the development of optimisation techniques [6–11], and the financial value of energy storage systems [9,12–15]. In addition, life cycle energy and greenhouse gas (GHG) emissions associated with pumped hydro energy storage (PHES), compressed air energy storage (CAES) and battery energy storage have been reported [16]. Reported round trip efficiencies for technologies suitable, or potentially suitable, for seasonal storage have ranged from 70 to 81% for PHES [4,16] and 50–66% for CAES ([17–19], to 36% for electrolysis and fuel cell systems [4].

The correlation of wind and solar generation with demand for the whole of Europe between 2000 and 2007 has been investigated, at monthly and hourly resolution, by Heide et al. [4]. For a 100% renewable electricity system, seasonal storage for a wind-only case was shown to be less than for a solar-only case. However, storage was minimised with a generation mix producing 55% of the energy from wind and 45% of the energy from solar. In a related pan-European electricity system study Rasmussen et al. [20] explored combinations of high-efficiency short-term (6 h) storage and low efficiency, hydrogen-based, seasonal storage, at hourly resolution over an 8-year period. It was found that incorporation of the short-term storage would reduce seasonal storage significantly in these

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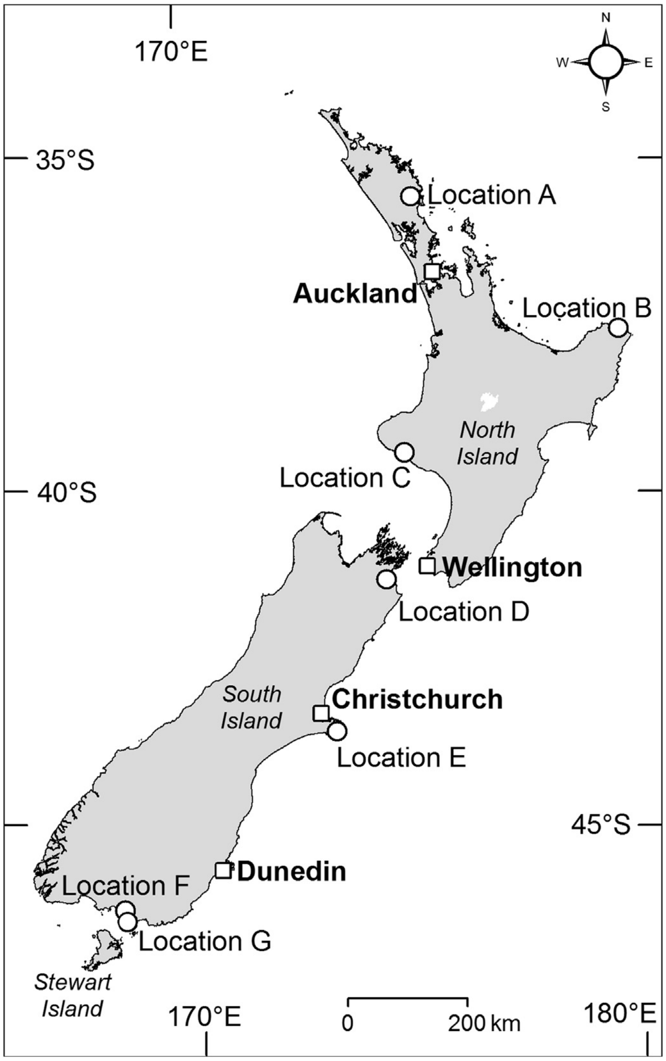

Fig. 1. Study locations.

circumstances. The energy outputs required to supply 100% of total demand to the entire USA electricity system, at monthly resolution, were determined by Converse [5], by scaling up reported wind and solar outputs between 2000 and 2007, from approximately 0.86% and 0.015% of annual demand respectively. Resulting annual storage values, expressed as a percentage of annual demand, and assuming 100% round trip efficiencies, ranged from 4.9% to 13.5% for wind, and from 21.3% to 31.7% for solar. For a 50:50 mix, the range was 7.5%–16.8%. In a modelling study of a 100% renewable electricity system, comprising wind and PV generation, for the contiguous states of the USA divided into 10 regions, and using 32 years of data at hourly resolution, Becker et al. [6] found energy storage to be less for solar-only than for wind-only scenarios, in contrast to the results of Converse. Assuming 100% round trip efficiencies, normalised storage values, as a fraction of annual demand, for the whole country were approximately 0.21 for PV only, 0.30 for wind only, and 0.18 for an optimal generation mix of 35% wind and 65% PV. On a regional basis, normalised storage values ranged from 0.13 to 0.52.

Whilst the literature has indicated the relative magnitudes of storage requirements where wind and PV generation are implemented on a country, or continental, scale, little is known about these relationships for more localised islanded systems. In addition, where generation and usage are geographically proximate, effects arising from widespread dispersion of generation and aggregation of demand will be absent, and optimal wind/PV generation mixes may, or may not, exist. Thus it is pertinent to investigate storage capacity requirements at these smaller scales. The specific objectives of this research were to: a) quantify the impact of wind and PV generation on annual energy storage capacities for islanded electricity systems; b) to investigate the sensitivity of energy storage capacity to variations in demand and resource patterns; and c) to determine whether hybrid wind/PV generation mixes require lower storage capacities than those for wind or PV generation individually.

2. Methods

2.1. Background

The research was conducted using New Zealand electricity demand and energy resources data. New Zealand is a temperate-climate country in which overall electricity demand peaks during the winter months of June, July and August [21]. Solar insolation is naturally lowest during this period. However, monthly average wind speeds have historically peaked during the spring and summer months of October, November, December and January [22]. The ratio of maximum to minimum monthly values was approximately 1.3:1 for wind speed and 4.1:1 for solar radiation. October through January were confirmed as peak months for wind generation in a subsequent study using a 19-year synthetic wind data set to model electricity output from established, and potential, wind farm sites [23].

2.2. Locations, study period and data sources

Six residential locations were selected in order to cover a range of latitudes and climatic conditions, from the sub-tropical north, through the more temperate central regions to the cooler southern

Table 1
Selected annual average climate characteristics for the period 2000–2011.

Location	Town	Climate station	Latitude[a] (°S)	Longitude[a] (°E)	Temperature (°C)	Global radiation (kWh/m^2.y)	Wind speed[b] (m/s)
A	Whangarei	Whangarei Aero	35.769	174.364	16.0	1441	–
		Kaitaia Aero[c]	35.067	173.287	–	–	4.5
B	Hicks Bay	Hicks Bay	37.564	178.314	15.0	1516	6.7
C	Hawera	Hawera	39.612	174.292	12.8	1465	5.2
D	Blenheim	Blenheim Aero	41.523	173.865	12.7	1521	–
		Cape Campbell[c]	41.731	174.274	–	–	7.6
E	Akaroa	Akaroa	43.809	172.966	12.8	1400	–
		Le Bons Bay[c]	43.946	173.119	–	–	6.2
F	Invercargill	Invercargill Aero	46.417	168.330	10.0	1217	4.7
G	“Farm Dairy”	Tiwai Point	46.587	168.376	10.7	1230	5.7

[a] Climate station location.
[b] At 10 m.
[c] Closest useable wind resource.