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Security of supply, energy spillage control and peaking options within a 100% renewable electricity system for New Zealand

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HIGHLIGHTS

- A 100% renewable electricity system was modelled over a 6-year period.
- Security of supply was demonstrated, including for the driest year since 1931.
- Stored energy spillage was controlled by using flexible base-load generation.
- Wind energy utilisation of 99.8% was obtained.
- Transitional use of fossil gas for peaking resulted in a 99.8% renewable system.

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ABSTRACT

In this paper, issues of security of supply, energy spillage control, and peaking options, within a fully renewable electricity system, are addressed. We show that a generation mix comprising 49% hydro, 23% wind, 13% geothermal, 14% pumped hydro energy storage peaking plant, and 1% biomass-fuelled generation on an installed capacity basis, was capable of ensuring security of supply over an historic 6-year period, which included the driest hydrological year on record in New Zealand since 1931. Hydro spillage was minimised, or eliminated, by curtailing a proportion of geothermal generation. Wind spillage was substantially reduced by utilising surplus generation for peaking purposes, resulting in up to 99.8% utilisation of wind energy. Peaking requirements were satisfied using 1550 MW of pumped hydro energy storage generation, with a capacity factor of 0.76% and an upper reservoir storage equivalent to 8% of existing hydro storage capacity. It is proposed that alternative peaking options, including biomass-fuelled gas turbines and demand-side measures, should be considered. As a transitional policy, the use of fossil-gas–fuelled gas turbines for peaking would result in a 99.8% renewable system on an energy basis. Further research into whether a market-based system is capable of delivering such a renewable electricity system is suggested.

1. Introduction

Global greenhouse gas (GHG) emissions patterns continue to increase rapidly (Peters et al., 2012) and evidence of anthropogenically-induced increases in the frequency of extreme events is now beginning to emerge e.g. (Kay et al., 2011; Pall et al., 2011; Rahmstorf and Coumou, 2011; Stott et al., 2011; Otto et al., 2012). The need to plan and implement sustainable energy systems in general, and renewable electricity systems in particular, is thus becoming increasingly urgent. Due to the variable nature of many renewable energy resources, increases in the proportions of both non-dispatchable and partially-dispatchable generation, will be a feature of such systems. It is thus beneficial to demonstrate scenarios on a country-by-country, or region-wide, basis in order to identify problems arising from various generation mixes, and to investigate potential solutions.

A number of authors have now reported modelling results for 100% renewable, or predominantly renewable, electricity systems (Ackermann et al., 2009; Mason et al., 2010a, 2010b; Wright and Hearps, 2010; Denholm and Hand, 2011; Troster et al., 2011; Van dePutte and Short, 2011; Elliston et al., 2012; Huva et al., 2012; Budischak et al., 2013). Modelling results for a 99% renewable European grid system, at hourly resolution over a 30 year period, were reported by Troster et al. (2011) and Van dePutte and Short (2011), following on from earlier work by Ackermann et al. (2009). Generation mixes comprising approximately 25–26% wind, 39–41%

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PV, 4–5% geothermal, 11–14% biomass, 4–5% concentrating solar power, 3% wave/tidal, 8–11% hydro and 1% gas on an installed capacity basis, were found to be technically and economically feasible. Wright and Hearps (2010) showed that 98% of Australian electricity demand over the period 2008–2009, modelled at half-hourly resolution, could be met with a generation mix comprising approximately 35% (42.5 GW) concentrating solar thermal (CST) generation with molten salt storage and 49% (60 GW) wind generation. In order to meet residual deficits, 4% (5 GW) of existing hydro and 12% (15 GW) of biomass-fired generation were utilised. In their simulation of grid operation in Texas, USA, Denholm and Hand (2011) modelled hourly wind, PV (a mixture of fixed and 1-axis tracking) plus concentrating solar power electricity generation over the period 2005–2006. These authors demonstrated an inverse relationship between system flexibility and the curtailment of variable renewables. They showed that a poor observed correlation between wind availability and demand patterns could be improved by the addition of solar generation, with a resulting decrease in curtailment. Further reduction in curtailment by the addition of energy storage, and potentially demand response measures, was shown. Elliston et al. (2012) modelled a 100% renewable electricity generation system for Australia, at hourly resolution, for the year 2010. A generation mix comprising 27% (23.2 GW) wind, 18% (15.6 GW) CST with thermal storage, 17% (14.6 GW) PV, 6% (4.9 GW) hydro, 28% (24 GW) biomass and 2% (2.2 GW) pumped hydro energy storage (PHES) was found to be capable of supplying demand, consistent with existing standards. Budischak et al. (2013) modelled renewable electricity system options at hourly resolution over the period 1999–2002 for a large region of the USA, using wind and solar generation. Up to 99.9% renewable electricity production was indicated, provided substantial over-capacity was specified. Key elements in each of these systems were: (a) the presence of rapid response peaking plant; (b) the absence or minimisation of inflexible base-load; (c) the presence of adequate storage. The need to accept of some degree of energy spillage, or curtailment, was also demonstrated.

For New Zealand, the present authors have previously demonstrated, at half-hourly resolution, how generation mixes comprising 53–61% hydro, 22–25% wind, 12–14% geothermal, 1% biomass and 0–12% additional peaking generation on an installed capacity basis could provide a 100% renewable electricity system on an energy and power basis (Mason et al., 2010a). Modelled systems were shown to provide security of supply, and to maintain net hydro storage, over a 3 year study period. However, several important issues remained unresolved. Maximum and minimum lake levels fluctuated more widely than those historically measured, increased hydro energy spillage occurred and significant wind energy spillage resulted, despite the overall wind energy utilisation level of 97.5%. Additional peaking plant capacity of 1167 MW, with a capacity factor of 1.1%, the equivalent in demand-side measures, or a combination of both, was indicated. However, the study period (2005–2007) did not include any particularly dry hydrological years. In an extension of this work (Mason et al., 2010b) we incorporated minimum hydro lake storage levels required in order to meet statutory security of supply risk criteria (NZ Government, 2006; NZEC, 2010). Wind installed capacities were then adjusted such that hydro lake levels always remained above a series of levels (known as the Minzone) representing a 1 in 60 year risk of the lakes running 'dry'. Considerable wind and hydro energy spillage resulted at a wind penetration of approximately 30%, and wind energy utilisation dropped to 94.6%.

At grid scale, pumped hydro energy storage (PHES) systems provide an established means of temporarily storing large amounts (GWh) of surplus energy for peaking purposes, as well as offering additional grid services, including frequency control (Boyle, 2004; Deane et al., 2010). Following a major increase in global PHES installed capacity between 1960 and 1990, partly in response to the need to complement increasing amounts of nuclear generation (Deane et al., 2010; Dursun and Alboyaci, 2010), there has been renewed interest in PHES systems over the last decade, primarily as a means of managing the increasing amounts of wind, and other variable renewables generation on electricity grids (Caralis and Zervos, 2007; Caralis et al., 2008, 2010; Connolly et al., 2010; Deane et al., 2010; Kaldellis et al., 2010; Kapsali and Kaldellis, 2010). Compressed air energy storage (CAES) systems provide a potential alternative e.g. (Denholm and Sioshansi, 2009; Cavallo, 2010), however adiabatic CAES efficiencies have been predicted to be lower than PHES and costs greater (Pickard et al., 2009a,2009b). In terms of peaking capacity only, gas turbines provide a rapid response alternative, e.g. (Andrews, 2007; Deane et al., 2010).

Flexible base-load operation may be provided by a range of generation systems, without the need for the rapid ramp rates required for peaking plants. Nuclear plants, on account of their slow response times (Pickard et al., 2009b), and coal plants with carbon capture and storage are considered unlikely to be suitable for load following duties. Geothermal, whilst typically operated as constant base-load generation, can be scheduled if required (IPCC, 2011; Mighty River Power (MRP), 2010, pers. comm.).

The purpose of this paper is to address issues of longer-term security of supply, energy spillage control, and peaking options, within a 100% renewable electricity system for New Zealand, arising from our prior two studies. The specific objectives are to: (a) provide an assurance of security of supply over a longer than 3 year time frame incorporating a significantly dry year; (b) eliminate or minimise hydro energy spillage; (c) minimise wind energy spillage; (d) identify and implement an appropriate peaking option. As background to the first objective, we note that national hydro inflows in New Zealand between November 2007 and mid-June 2008 were the lowest recorded since 1931 (Hunt et al., 2008). During the winter of 2008, South Island lake storage levels were deemed to be critically low, with storage levels falling below the Minzone for a total of 65 days. Our present study incorporates this period.

2. Methods

2.1. Data sources

Electricity generation data in kW for each half-hour were obtained from the NZ Electricity Authority (NZEA, 2011) and classified by generation fuel type. Daily New Zealand hydro lake storage levels and inflows in GWh, plus hydro storage capacities, were sourced from a generator, and a local electricity information company (Meridian Energy, 2005; COMIT, 2009; NZX, 2011). For modelling purposes, a total storage capacity of 4390 GWh was adopted, and the lake system was treated as a single reservoir. Minimum zone (Minzone), emergency zone (Ezone), and subsequently, hydro risk data, which supplanted the former two measures from 2009 onwards, were sourced from the New Zealand Electricity Commission (B. Bull; pers. comm.). Hydro risk curves for 2009–2010 were linearly interpolated in order to obtain the same risk level as given by the Minzone, whilst the Ezone was given directly by the 10% hydro risk data.

2.2. Study period

The period 1 January 2005 to 31 December 2010 was used. This included the particularly dry year of 2008. As previously, generation data prior to 2005 were rejected because of incomplete coverage across the electricity sector.