Transitioning to a 100% renewable electricity generation system: balancing the roles of wind generation, base-load generation and hydro storage.

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Abstract

In this paper we demonstrate how various combinations of wind and new base-load generation can be used to ensure that hydro storage levels in a 100% renewable electricity generation system remain within historically acceptable values. Three levels of new base-load were modelled, 500, 1000, 1500MW, resulting in required wind capacities of 3266, 1801 and 400MW respectively. The magnitude and frequency of deficits in supply, and the amount of hydro spillage decreased with decreasing wind capacity. A tension is thus revealed between the plentiful wind resource in New Zealand and the impact on both peaking power requirements and hydro spillage. Demand-side measures are discussed. We conclude that transitioning to a fully renewable electricity generation system requires careful consideration of the types of generating plant in the mix, peaking capacity, available storage and implementation of demand-side management.

Introduction

The New Zealand electricity and heat sector generated 8.8% of total greenhouse gas (GHG) emissions in 2007, primarily due to the combustion of coal and gas in thermal electricity generation plants (MfE, 2009). At this time fossil-fuelled installed capacity amounted to 3178 MW, or 32% of the total generation capacity, supplying 33% of electricity that year (MED, 2009). Recently, Mason et. al. (2010) have shown how a 100% renewable electricity generation system in which all fossil-fuelled generation is replaced with wind and geothermal resources, plus additional renewables-fuelled peaking plant and/or demand-side measures, could operate in New Zealand, using historic electricity generation data for the period 2005-2007. However, this system resulted in greater fluctuations in hydro lake storage levels than historically observed, giving both increased hydro spillage, and considerably lower storage values. In addition, the increased amount of wind generation (approximately 6.8 times the installed capacity present at the end of 2007) required additional peaking plant, and/or load-shifting, to be specified, in order to meet residual deficits in supply.

New Zealand’s hydro generation system has a relatively low energy storage capacity compared to that available in other hydro-dominated systems. For example, Norway which generated 98.6% of its electricity from hydro in 2008, has 84,147 GWh reservoir storage (Nordel, 2008), compared to New Zealand’s approximately 4400 GWh. When all New Zealand lakes are full this amounts to approximately 34 days reserve at peak winter demand (approximately 130 GWh/d in 2007), assuming zero inflow. In the winter of 2008, South Island lake storage levels were deemed to be critically low, and a combination of industrial and domestic power savings measures were introduced (Bradley, 2008; NZPA, 2008). National hydro inflows between November 2007 and mid-June 2008 were the lowest recorded since 1931 (Hunt et. al., 2008). Similar crises arose in 1989, 1992 (when blackouts occurred), and 2003. Whilst the previously reported simulations showed that no problems would have occurred during the study period, we believe that the preceding trends and the minima obtained would, without the benefit of hindsight, have created cause for concern.

The New Zealand Electricity Commission (NZEC), under the Electricity Act (1992), and also as directed by Government Policy Statements (GPS) on Electricity Governance is required:

> "…to use reasonable endeavours to ensure the security of electricity supply" (NZEC, 2010a).

In the context of New Zealand's hydro-dominated system, threats to security of supply are initially signalled by the amount of reserve hydro storage available at any time. Acceptable storage levels vary throughout the year, according to expected inflows, electricity demand, and system operation and can be translated into a risk factor. In a GPS issued in October, 2006 the risk factor was specified within the following security objective statement:

> "…use reasonable endeavours to ensure security of supply in a 1 in 60 dry year without assuming any demand reduction from emergency conservation campaigns." (NZ Government, 2006).

The NZEC has traditionally calculated "minzone" hydro storage levels in order to signal when "careful management of the generating system" is required. If the "minzone" is reached, there is a 1 in 77 chance that the annual hydro inflow pattern will result in the lakes running dry if no action is taken (NZEC, 2010b). In addition, an "Emergency Zone" with a 1 in 10 year risk of the hydro lakes running dry has been calculated for certain years (NZEC, 2010b). In 2009, the "minzone" analysis was replaced with hydro risk curves in which hydro storage levels associated with a range of risk factors were calculated. When signalled, further action on the part of the NZEC involves the use of three main tools:

> "a) procuring reserve energy; b) running conservation campaigns; c) oversight of any rationing processes." (Hunt et al., 2008).

In this paper we present modifications of the 100% renewable generation mix previously reported by Mason et. al. (2010), which maintain hydro lake storage levels at or above "minzone" levels during the study period. The aims of the research were to determine: a) levels of wind generation and/or other generation required to give chosen lake storage minima; b) the impacts on additional peaking plant requirements, on hydro spillage and on storage capacity; c) the potential role of demand-side management in mitigating the impacts of these changes.

Methods

Data sources

Electricity generation data in kW recorded each half-hour, classified by generation fuel type, were obtained from the NZ Electricity Commission (NZEC, 2009). Daily New Zealand hydro lake storage levels and inflows in GWh, plus hydro storage capacities, were sourced from COMIT and Meridian Energy (COMIT, 2009; Meridian Energy, 2005). For modelling purposes, a total storage capacity of 4390 GWh was adopted, and the lake system was treated as a single reservoir. "Minzone" data were obtained from the NZEC (B. Bull; pers. comm.).

Study period

The period 1 January 2005 to 31 December 2007 was used. Generation data prior to 2005 were rejected because of incomplete coverage across the electricity sector, whilst at the time the available data set from April 2008 onwards omitted generation plants < 10 MW installed capacity (NZEC, 2009), thus limiting full year coverage to 2005-2007.

Modelling approach

The modelling approach was based on step 4 of the methodology of Mason et. al. (2010), in which the modelled electricity system comprised hydro and biomass generation at their historic capacities, with variable hydro scheduling, augmented by additional wind and geothermal generation. In the original study additional wind generation was used to return final hydro lake storage to the historic level at the end of the study period. Minimum hydro storage was then reported. The reader is referred to Mason et. al. (2010) for further details.

In the present study, wind and/or new base-load generation capacities were adjusted to ensure that the "minzone" was not entered at any time, and final hydro storage levels were then observed. New base-load was specified at three levels (500, 1000 and 1500 MW) and the required wind capacity to meet the "minzone" criterion then calculated. Key modelling values are listed in Table 1.

Model outputs were: a) half-hourly generation by primary energy fuel type, and b) hydro lake system storage levels. These are reported as surpluses and deficits between modelled generation and historic demand, and as modelled and historic hydro lake storage.

Table 1: Key modelling values and assumptions

Parameter	*Units*	*Value*	**Comments**
Hydro capacity	MW	5347.0	Total nameplate
	MW	4540.9	Maximum observed
	MW	974.1	Minimum observed
Ramping rate	MW/half-h	685.698	Maximum observed
Hydro storage minima	GWh	Variable	NZEC "minzone"
Added base-load capacities	MW	500, 1000, 1500	Additional to existing capacity (431.0 MW)

Capacity credit and wind penetration

Capacity credit values for wind were calculated from the following expression (after Milborrow, 2007):

$$CC = \left[\frac{P_{fossil} - P_{backup}}{\Delta P_{wind}} \right]$$

where: CC = capacity credit; P_{fossil} = fossil fuelled thermal capacity displaced; P_{backup} = renewable backup capacity added; ΔP_{wind} = wind installed power added.

Three expressions for wind penetration (WP) were employed, based on installed capacity, average annual energy and instantaneous power respectively.

Results and Discussion

Minimum prior storage

Previous modelling indicated a minimum hydro lake storage value of 395 GWh, compared to the existing (historic) system minimum of 1548 GWh (Mason et. al., 2010). Fig. 1 shows how this generation mix resulted in the modelled hydro storage entering the "minzone" at around day 500 (early May, 2006) and remaining there for over 100 days (until early September, 2006).

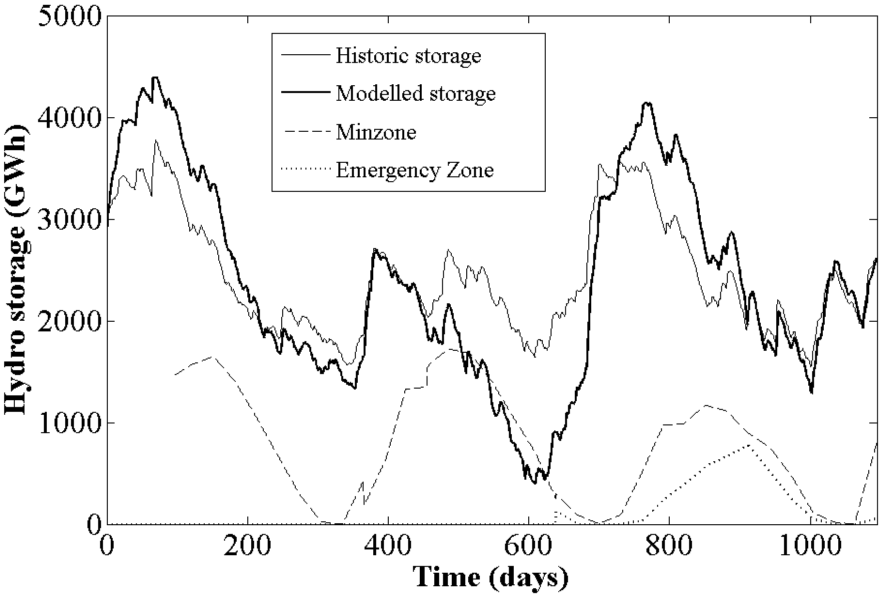

Fig. 1: Hydro lake storage levels from step 4 in Mason et. al. (2010)

Generation mixes to avoid entering the "minzone"

In scenario 1, a combination of 3266 MW wind and 931 MW geothermal plus new base-load capacity enabled the "minzone" criterion to be met (Table 2; Fig. 2a). This level of wind penetration (33.6%) resulted in a maximum deficit of 1432.9 MW, and wind energy spillage of 1823 GWh (Table 2). Consequent impacts on hydro storage are shown by the water spillage of 1070 GWh and final storage level of 3614 GWh.

Table 2: Model parameters, inputs and outputs

Parameter	*Units*	*Existing system*[a]	*Scenario 1*	*Scenario 2*	*Scenario 3*
Installed capacity:					
Hydro	MW	5347.0	5347.0	5347.0	5347.0
Wind	MW	219.0	3266.0	1801.0	400.0
Geothermal	MW	431.0	431.0	431.0	431.0
New base-load	MW	0	500.0	1000.0	1500.0
Biogas	MW	23.7	23.7	23.7	23.7
Wood thermal	MW	79.2	79.2	79.2	79.2
Fossil fuels	MW	2878.4	0	0	0
Total	MW	8878.3	9646.9	8681.9	7780.9
Model outputs (over 3 y):					
Hydro	GWh	69,872	67,802	68,700	69,718
Wind	GWh	2,145	31,710	18,097	4,090
Geothermal	GWh	9,206	9,206	9,206	9,206
New base-load	GWh	0	13,140	26,280	39,420
Biogas	GWh	389	389	389	389
Wood	GWh	844	844	844	844
Fossil fuel	GWh	41,235	0	0	0
Total	GWh	123,691	123,091	123,516	123,667
Energy spill	GWh	0	1823	389	13
Unmet demand	GWh	0	600	175	25
Additional water spill	GWh	0	1070	534	240
Initial hydro storage	GWh	2841	2841	2841	2841
Final hydro storage	GWh	2611	3614	3251	2527
Minimum storage	GWh	1548	857	803	760
Maximum power deficit	MW	0	1432.9	940.2	448.0
Maximum power surplus	MW	-	1785.2	1023.4	327.1
WP (installed capacity)	%	2.5	33.9	20.7	5.1
WP (energy share)	%	1.7	25.8	14.6	3.3
WP (instantaneous – max)	%	5.8	62.2	41.5	11.2
Wind useful energy	%	-	94.6	97.9	99.7

Note: [a] actual system in 2005-2007

In scenario 2, an increase in geothermal plus new base-load capacity to 1431 MW, enabled the “minzone” criterion to be met using a reduced amount of 1801 MW wind generation (Table 2; Fig. 2b). At this level of wind penetration (20.7%) the maximum deficit dropped to 940.2 MW and wind energy spillage reduced to 389 GWh (Table 2). In this case the water spillage was reduced to 534 GWh and final storage level was 3251 GWh.

Finally in scenario 3, a total geothermal plus new base-load capacity of 1931 MW, in combination with 400 MW wind was sufficient to meet the “minzone” criterion (Table 2; Fig. 2c). Here the level of wind penetration was 5.1%, giving a maximum deficit of 448 MW and wind energy spillage of 13 GWh (Table 2). Water spillage was 240 GWh, with a final storage level of 2527 GWh.

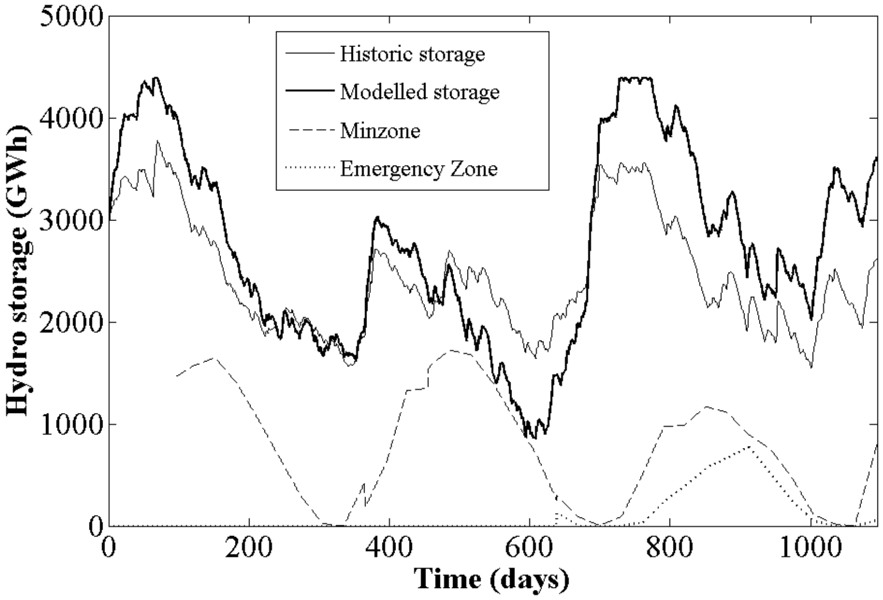

Fig. 2a: Hydro lake storage for scenario 1

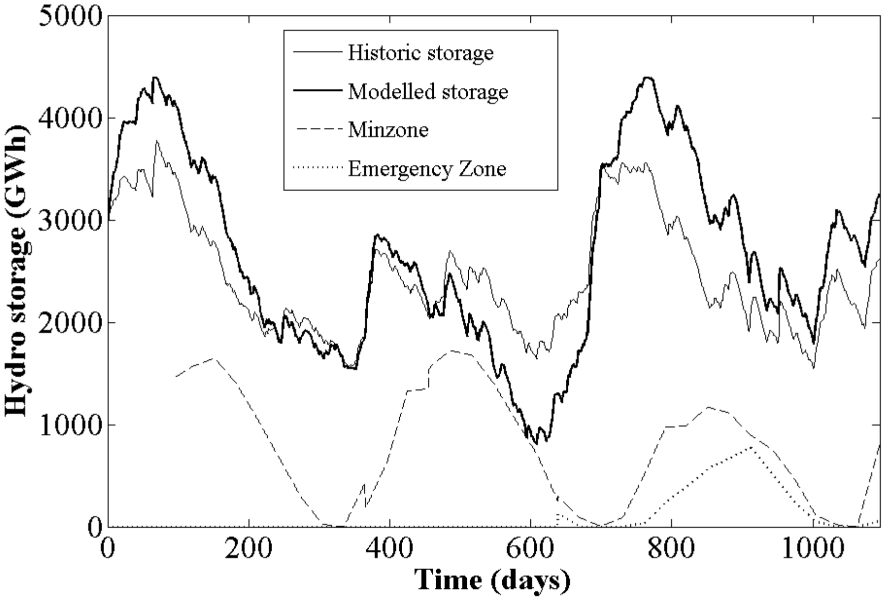

Fig. 2b: Hydro lake storage for scenario 2

Overall, decreasing wind penetration and increasing base-load generation resulted in a reduction in the magnitude of power deficits and surpluses, and fewer periods in which they occurred (Fig. 3a-c). A significant observation here is that although the peak deficits were relatively large (448-1443 MW), the required energy was very low. Thus, were additional peaking plant specified and only utilised for this purpose, it would operate with very low capacity factors, ranging from 1.59 to 0.02 in the three scenarios explored. Hydro spillage decreased from scenario 1 to scenario 3, and more hydro energy was utilised, as reflected in the progressively lower storage levels remaining at the end of the study period. Wind energy utilisation in scenario 1 was 94.6% of that generated, despite the apparently high spillage, and improved utilisation was observed in scenarios 2 and 3.

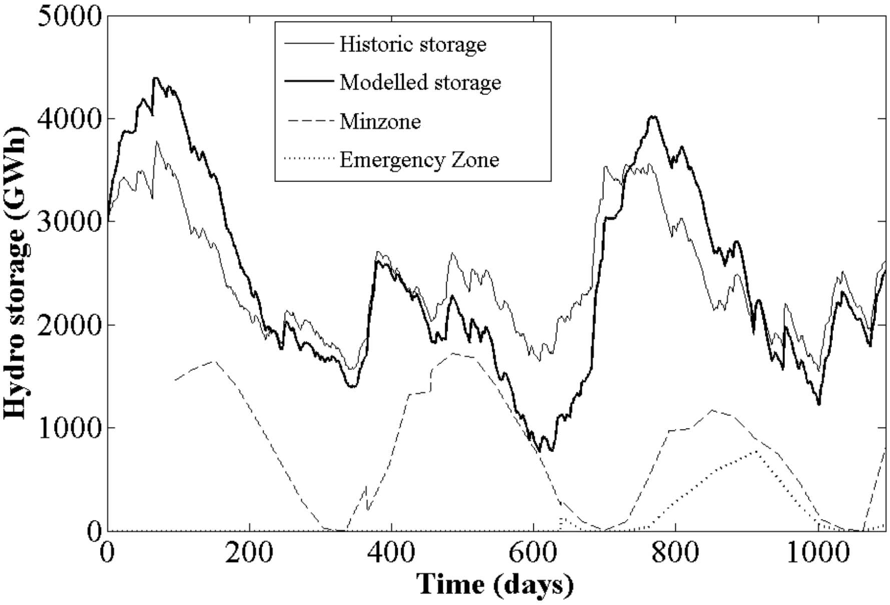

Fig: 2c: Hydro lake storage for scenario 3

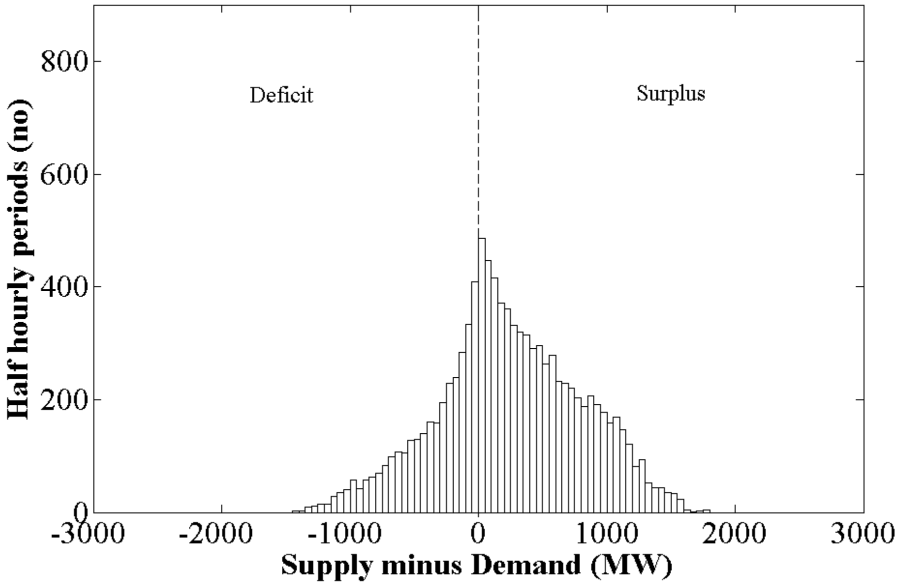

Fig. 3a: Deficit and surplus generation for scenario 1

Deficits and demand-side management

Generation mixes incorporating additional peaking plant are shown in Table 3. Whilst this approach to satisfying the deficits makes only small differences to the system parameters shown, it requires large plant capacity to be idle for most of the time. In contrast to the capacity factors shown, wind generation in New Zealand has a typical capacity factor of 40%, with hydro closer to 50%.

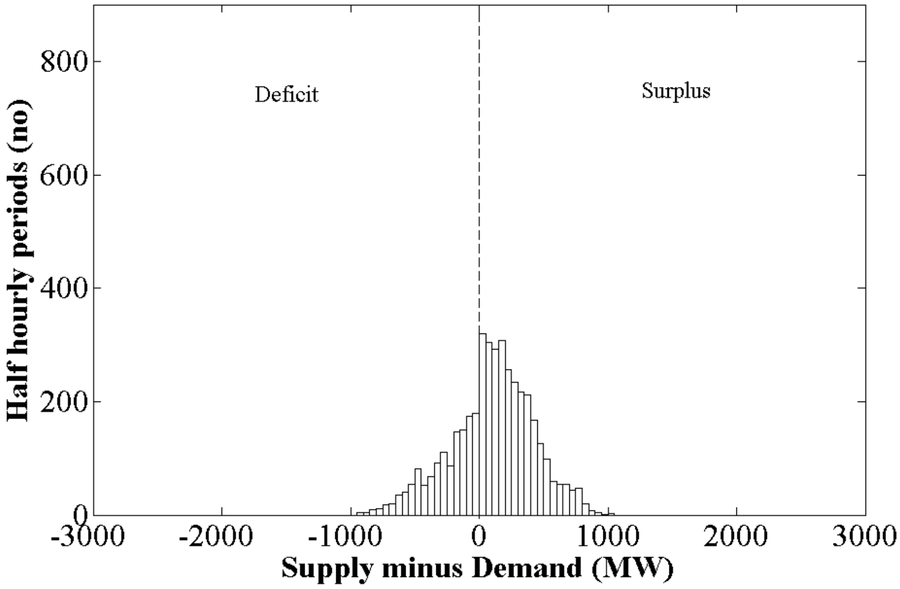

Fig. 3b: Deficit and surplus generation for scenario 2

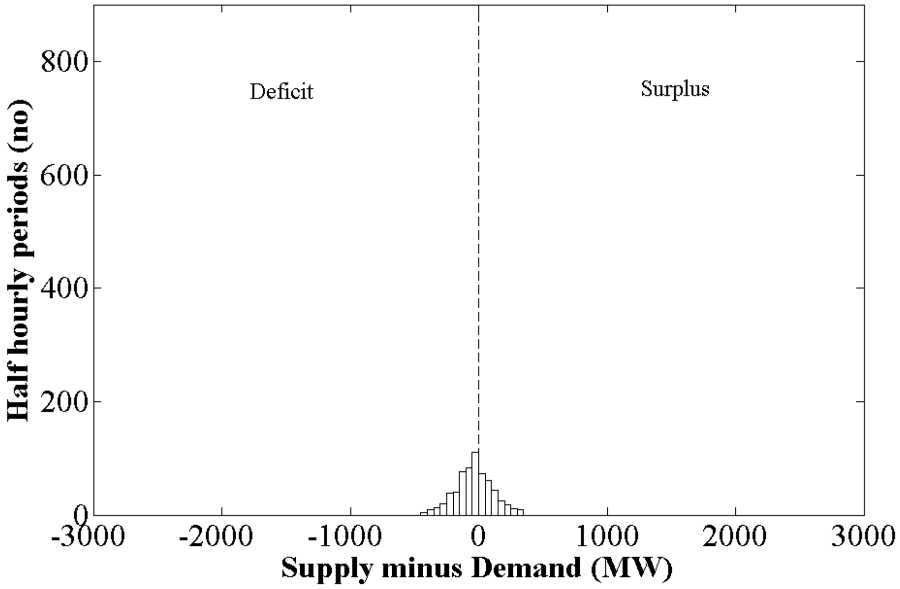

Fig. 3c: Deficit and surplus generation for scenario 3

In contrast, demand-side management involves minimal capital outlay, no additional transmission and makes better utilisation of existing generation plant. Load shifting can be made economically attractive to users, and is employed in other large-scale generation systems such as the UK for example (Andrews, 2007). It has been estimated that 450 MW domestic hot water load shifting is readily achievable in New Zealand (Mason et. al., 2010). Further possibilities may exist in the industrial sector. New Zealand has two steel mills, one aluminium smelter, and a large number of cool stores in the meat and dairy industries, all of which have the potential to shed loads for short periods of time. Further research is required to determine the existing level of load shifting already practised in New Zealand, and the potential to move towards the approximately 450-1430 MW capacity indicated in this study.

Table 3: Generation mix characteristics with additional peaking plant

Parameter	*Units*	*Scenario 1*	*Scenario 2*	*Scenario 3*
Installed capacity:				
Hydro	MW	5347.0	5347.0	5347.0
Wind	MW	3266.0	1801.0	400.0
Geothermal plus new base-load	MW	931.0	1431.0	1931.0
Biofuels	MW	102.9	102.9	102.9
Additional peaking plant	MW	1432.9	940.2	448.0
Total	MW	11097.8	9622.1	8228.9
Model outputs (over 3 y):				
WP (installed capacity)	%	29.5	18.7	4.9
WP (energy share)	%	25.6	14.6	3.3
Wind capacity credit	%	31.0	59.3	514.1
Peaking plant capacity factor	%	1.59	0.71	0.02
ALOL[a]	d/y	0	0	0

Note: [a] actual loss of load

Wind capacity credits

Capacity credit values for wind indicate the degree of backup capacity required in order to balance the system at all times. The capacity credit values for scenarios 1 and 2 reflect the amounts of additional base-load generation added, giving total installed capacities greater than for the historic system, as well as its operation at an assumed capacity factor of 100%. In the case of scenario 3, the overall system installed capacity was considerably less than for the historic system, resulting in a capacity credit much greater that 100%.

Storage

The New Zealand hydro lake system provided virtual storage for wind energy in the scenarios explored. Wind was operated as “must run” generation, with hydro responding by ramping down as wind ramped up and vice versa. Whilst acceptance of a degree of hydro energy spillage is an unavoidable consequence in this situation, we suggest that minimisation of such spillage is therefore an important design objective.

Increasing storage capacity will be of value only if the water saved can be subsequently utilised. Further research is required to determine the magnitude and impact of any proposed increase in capacity of the New Zealand system.

Transition issues

This research has demonstrated the impact of 3 different combinations of wind and base-load generation, within a 100% renewable electricity system, whilst ensuring that hydro lake storage remained outside the “minzone” during the study period. Confidence that security of supply can be maintained by such a system is therefore high, and no worse than with the existing system. However, each generation mix was shown to have different outcomes, and choices in peaking options were not resolved. In planning a transition from the present system to a fully renewable system, we identify the following issues to be addressed: a) the balance between wind generation and base-load generation; b) the role of hydro storage; and c) the role of demand-side measures; d) peaking plant options.

In relation to wind generation New Zealand is fortunate to possess one of the best wind resources in the world, with capacity factors typically around 40%, and up to 50% in the case of the Brooklyn turbine in Wellington. In contrast, Denmark, a world leader in wind energy implementation, experiences 25-30%. Wind is also considered to be one of the cheapest forms of generation in New Zealand at present (Smales, 2010) and the potential is considerable, with up to 6600 MW projected to be available in a recent study (EECA, 2009). Thus it seems appropriate to make good use of this resource. New Zealand's geothermal resources are also considerable, however the EECA (2009) study identified only 635 MW of new capacity available. Geothermal generation has the advantage that it can be, and commonly is, run to provide near-constant base-load, at capacity factors approaching 100%. An alternative source of base-load generation may be found in new hydro resources. The EECA (2009) study reported an estimated 4680 MW available for development. Given the additional peaking requirements generated by increased wind penetration, careful consideration must be given to the balance between new wind generation, of which there is potentially a plentiful supply, and new base-load generation, which appears somewhat constrained by either the quantity of the resource (geothermal), or the nature of the resource (run-of-the-river hydro and/or reservoir hydro). Currently, peaking power is supplied by hydro, biogas and natural gas plants. Transition plans should consider the potential to reduce peaks, the ability to generate producer gas from biomass resources and the role of continued use of natural gas for a specified period.

Should more hydro storage be planned? This is a key topic for discussion, but given the likely expense, we suggest that careful consideration be given to alternative measures which would enable optimum use of the hydro resource. These include installing additional generating capacity in the system, and ensuring that hydro is preferred over less environmentally friendly generation options. Any transition plan must also incorporate demand-side management, in order to minimise peaks in demand (power) and, ultimately encourage lower energy consumption overall.

Conclusions

Three different generation mixes were found to be capable of providing a 100% renewable electricity system for New Zealand, whilst meeting existing "minzone" criteria for ensuring security of supply. As wind penetration decreased from 29.5% to 18.7% to 4.9%, and new base-load was added accordingly, the magnitude and frequency of supply deficits needing to be met by peaking plant and/or demand-side measures decreased substantially. Hydro spillage also decreased with lower levels of wind penetration. Since wind resources are plentiful and relatively cheap in New Zealand, new geothermal reserves are limited and new hydro generation has potential development constraints, transitional planning must consider the appropriate balance between the amount of wind generation in the system and the implications for peaking measures. The role of hydro storage was found to be significant, but further research is required to determine whether building additional capacity is justified. Demand-side measures offer potential to minimise peak power requirements at low cost, but further investigation is needed to ascertain the potential to deal with the 450-1430 MW peaks identified in this study.

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