Summary of Findings

New Zealand Wind Integration Study

Goran Strbac, Danny Pudjianto, Anser Shakoor, Manuel J Castro

Imperial College London

Guy Waipara, Grant Telfar

Meridian Energy Limited

April 2008

Challenges of integrating wind generation

- Generation capacity adequacy
  - How “reliable” is wind generation as a source? How much conventional capacity can it displace? What are the system integration capacity costs and benefits?
- Real time system balancing
  - What are the needs for flexibility and reserve? What are the costs? What is the role of storage, demand side participation and interconnectors?
- Transmission network requirements
  - How much new transmission capacity is required to efficiently transport wind power?
- System stability
  - What is stability performance of the system with new forms of generation? Can this technology contribute to improving stability?
- Role of enabling technologies
  - Can storage and responsive demand have a role in facilitating integration of wind generation? Are these solutions competitive? What are the drivers of value? What new tools are required to support system management with wind generation?
- Technical, commercial and regulatory framework
  - Are the technical, commercial and regulatory arrangements appropriate for a system with significant contribution of wind? Are the Grid Codes and Standards appropriate? Are the arrangements for access to transmission networks appropriate? Are non-network solutions to network problems competitive? Does the market reward flexibility adequately?

Wind Integration in NZ: Background

- Widespread expectation that wind power generation will become an increasingly significant proportion of overall generation mix in the future of NZ electricity system
- Wind Integration questions addressed include
  - Capacity value of wind (ability of wind power to displace thermal generation)
  - Increased reserves and flexibility requirements to deal with uncertain and variable nature of the outputs of wind generation
  - Location and remoteness of this generation relative to centres of demand
- Key objective of this work was to develop methodologies for providing detailed quantitative assessments of the system costs of integrating various levels of wind power into the NZ electricity system
  - The analysis shows that wind variability increases the need for operating reserve and associated generation capacity to manage balance of demand supply

System Cost Components of Wind Integration

1. Additional system reserve cost
   - Additional requirements for instantaneous and frequency keeping reserves
   - Additional requirements for scheduling reserve
2. Additional system generation capacity cost
   - Wind generation is primarily an energy source with limited ability to provide reliable generation capacity at times of peak demand
3. Transmission constraints and reinforcement cost driven by wind power*

*Reactive power reserves, voltage control and stability performance are not considered, as the cost of mitigation options are an order of magnitude lower.

Summary of Key Findings - 1

- Unlike thermal generation based power systems in which capacity value of wind is determined by the availability of wind during peak demand conditions, the capacity value of wind in New Zealand is:
  - High due to high load factors of wind resource
  - Enhanced by the presence of hydro generation
  - Reduced by the large variations in relatively small period of time that need increased amounts of reserves
- Additional capacity costs attributed to wind generation:
  - 2010 costs (1.7 to 2.7 $/MWh) are higher than the 2020 costs (1.3 to 2.2 $/MWh) due to the different NI-SI interconnector (2010 – 1000MW and 2020 1500MW) which increases the sharing of reserve capacity and diversity of wind generation.
  - 2020 – 2030 rise in wind capacity cost (to 6.2 -9 $/MWh) is primarily driven by larger capacity reserve requirements to accommodate larger wind forecasting errors at higher penetration levels

Summary of Key Findings - 2

- Hydro increases capacity credit of wind. However, at higher penetrations the contribution of hydro to firm up wind power reduces
- Capacity credit of wind generation in the NZ's hydro dominated system is higher than in the other thermal based systems, however, it also declines with rise in wind penetration level
- Capacity values for wind are not effected by hydro (dry) conditions although the overall capacity requirements increase with low availability of hydro energy
- The low production of wind for days is found not to effect the capacity value of wind as this can be compensated by the flexible hydro energy with presence of large hydro reservoirs
- The role of the interconnector changes. Over time, interconnector will become critical for maintaining security of supply in the South Island.

Summary of Key Findings - 3

- Additional reserves are needed to cover the unpredictability of wind power
  - Instantaneous reserve, up to 30 min provided by synchronised generators
  - Frequency keeping reserve to cover 1 hour of wind variability is assumed to be provided by synchronised reserve
  - Scheduling reserve to cover 4-6 hours of wind variability is assumed to be provided by synchronised + standing reserve
- The quantity of wind reserve component increases with rise in wind penetration
- Provision of scheduling reserve up to 4-6 h time horizon
  - For low wind penetration (2010), hydro will be the primary source of scheduling reserve
  - For high wind penetration (2020 &2030), it is desirable to use flexible standing power plants for dealing with scheduling time horizons

Summary of Key Findings - 4

- The cost of additional reserve to deal with forecasting error of wind for several scenarios have been quantified
  - Instantaneous reserve, up to 30 min provided by synchronised generators
  - For low penetration (4.9% in 2010) , the cost of additional reserves is around 0.19 $/MWh of wind energy
  - The cost of additional reserves increases to 2.42 $/MWh of wind energy by 2030 under a high wind penetration scenario (17.9%)
- The primary source of synchronized reserve remains to be hydro but in future the contribution from interruptible load and thermal plants will increase
- Some curtailment of wind and hydro energy is observed in high wind penetration scenarios. This occurs during a combination of low demand, wet hydro conditions and high wind conditions

Summary of Key Results

	2010	2020	2030
Installed wind power capacity (MW)	634	2,066	3,412
Wind power (GWh)	2,285	6,724	10,797
Capacity credit of wind (%)	32	29	15
Max. Instantaneous Reserve (MW)	565	691	912
Max. Frequency Keeping (MW)	309	540	866
Max. Standing Reserve (MW)	46	377	566
Capacity cost ($/MWh of wind)	1.7 - 2.5	1.3 - 2.0	6.2 - 9.3
Reserve cost ($/MWh of wind)	0.19	0.76	2.42
Total cost attributed to wind ($/MWh of wind)	**1.89 - 2.69**	**2.06 - 2.76**	**8.62 - 11.72**

NZ Electricity System:
Future Scenarios Under Study

Scenarios

- Three scenarios correspond to future generation in 2010,2020 and 2030 were constructed to represent increasing levels of wind penetration up to 18% of electricity consumption in 2030
- Demand growth was assumed to be about 1.25%-1.5% p.a.
- Hydro inflows profiles were developed using SPECTRA
  - Daily run of river profiles
  - Weekly reservoir release profiles
- 2005 and 2006 wind profiles were assessed. 2005 wind profiles were used in the main studies as they represent a lower wind year

Future Wind Scenarios

High Wind 2010
NI:432 MW
SI:203 MW
NZ:634 MW

Location	Island	MW	GWh PA	Avg LF
Otago	SI	144.0	492	39.0%
Manawatu	NI	7.0	28	45.0%
Manawatu	NI	19.5	77	45.0%
Wellington	NI	142.6	573	45.9%

Very High Wind 2020
NI:1434 MW
SI:632 MW
NZ:2066 MW

Location	Island	MW	GWh PA	Avg LF
Otago	SI	144.0	492	39.0%
Manawatu	NI	7.0	28	45.0%
Manawatu	NI	19.5	77	45.0%
Wellington	NI	142.6	573	45.9%
Wellington	NI	94.3	363	44.0%
Hawke's Bay	NI	48.0	179	42.5%
Hawke's Bay	NI	150.0	484	36.9%
Central	NI	100.0	350	40.0%
Manawatu	NI	150.0	565	43.0%
Wairarapa	NI	90.0	323	41.0%
Northland	NI	102.5	359	40.0%
Taranaki	NI	99.0	361	41.7%
Northland	NI	68.8	241	40.0%
Wellington	NI	100.0	365	41.7%
Otago	SI	261.0	892	39.0%
Southland	SI	168.0	589	40.0%

Very High Wind 2030
NI:2215 MW
SI:1197 MW
NZ:3412 MW

Location	Island	MW	GWh PA	Avg LF
Otago	SI	144.0	492	39.0%
Manawatu	NI	7.0	28	45.0%
Manawatu	NI	19.5	77	45.0%
Wellington	NI	142.6	573	45.9%
Waikato	NI	44.0	135	35.0%
Manawatu	NI	150.0	526	40.0%
Wellington	NI	94.3	363	44.0%
Hawke's Bay	NI	48.0	179	42.5%
Hawke's Bay	NI	150.0	484	36.9%
Central	NI	100.0	350	40.0%
Manawatu	NI	150.0	565	43.0%
Wairarapa	NI	90.0	323	41.0%
Northland	NI	102.5	359	40.0%
Hawke's Bay	NI	111.0	389	40.0%
Otago	SI	100.0	377	43.0%
Otago	SI	261.0	892	39.0%
Taranaki	NI	99.0	361	41.7%
Northland	NI	250.7	878	40.0%
Auckland	NI	225.0	788	40.0%
Northland	NI	68.8	241	40.0%
Otago	SI	100.0	359	41.0%
Wellington	NI	100.0	365	41.7%
Otago	SI	150.0	512	39.0%
Canterbury	SI	215.0	659	35.0%
Southland	SI	168.0	589	40.0%

Source: www.nzwindfarms.co.nz

Capacity Value and Additional Capacity Costs of Wind Generation

NZ Generation Capacity Analysis

1. Assessment of optimal overall generation capacity requirements in each future wind scenario
2. Capacity credit evaluation of wind generation
3. Evaluation of additional capacity cost of wind generation
4. Sensitivity studies include*
   - A. Wind forecasting errors
   - B. Impact of hydro conditions (Dry/Average/Wet)
   - C. Impact of interconnector size and its reliability
   - D. Impact of wind diversity

* sensitivity analysis are not included in this executive summary but will be included in the final report

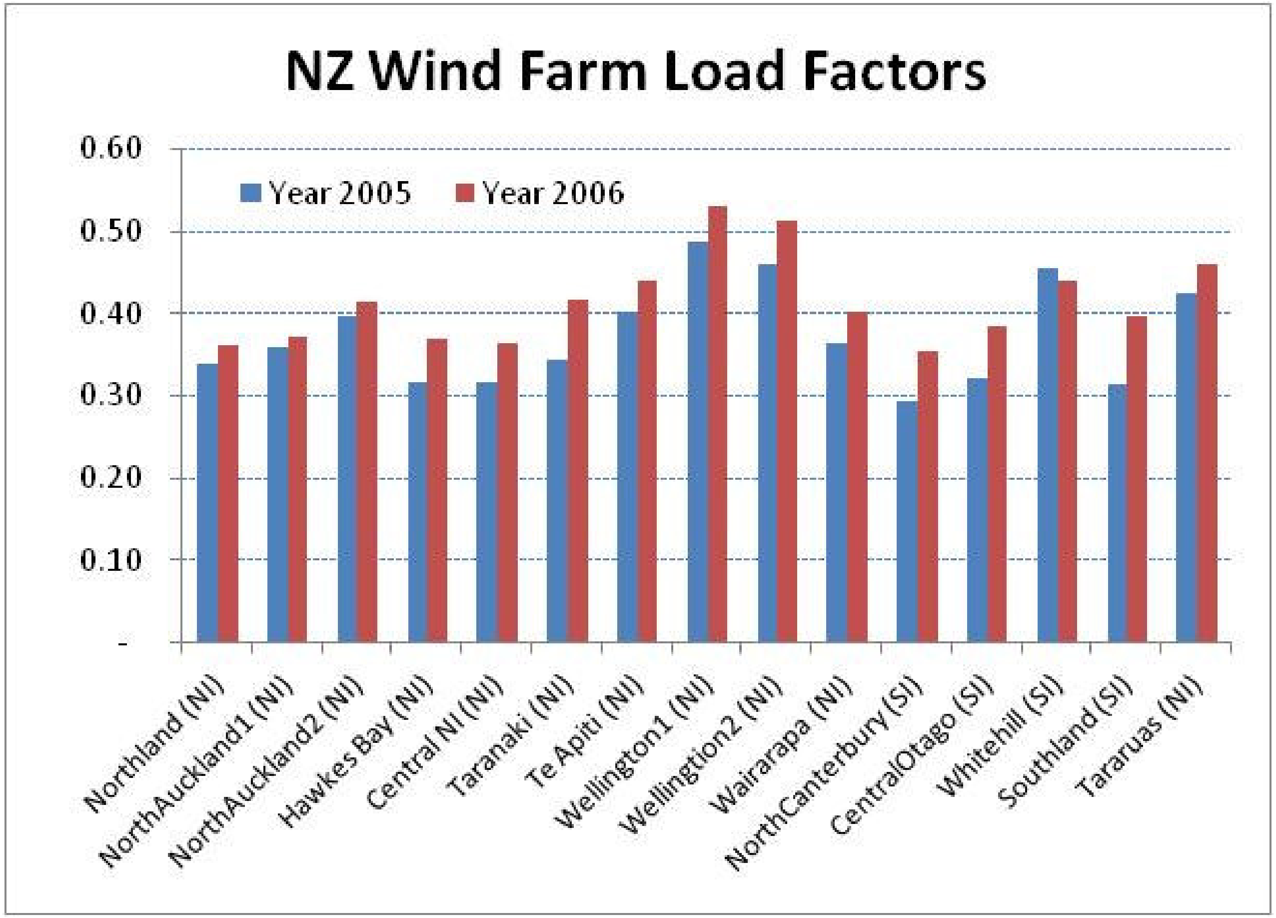
Capacity Modelling Approach – 1

- The system reliability criterion for capacity adequacy applied in this study is Loss of Load Expectation (LOLE) with a conservative target of 8 hours/year
- Hydro plants are represented as Island aggregated units. Island aggregated profiles of each of run-of-river and reservoir type hydro energy are used
- Hydro is modelled as a fully reliable generation
- The dispatch of hydro power is obtained optimally to minimize the overall thermal capacity requirements of the system - this serves as the objective function of the capacity assessment model
- Weekly reservoir releases (from the SPECTRA model) are used in the dispatch programme - water is used within each week and cannot be shared between weeks

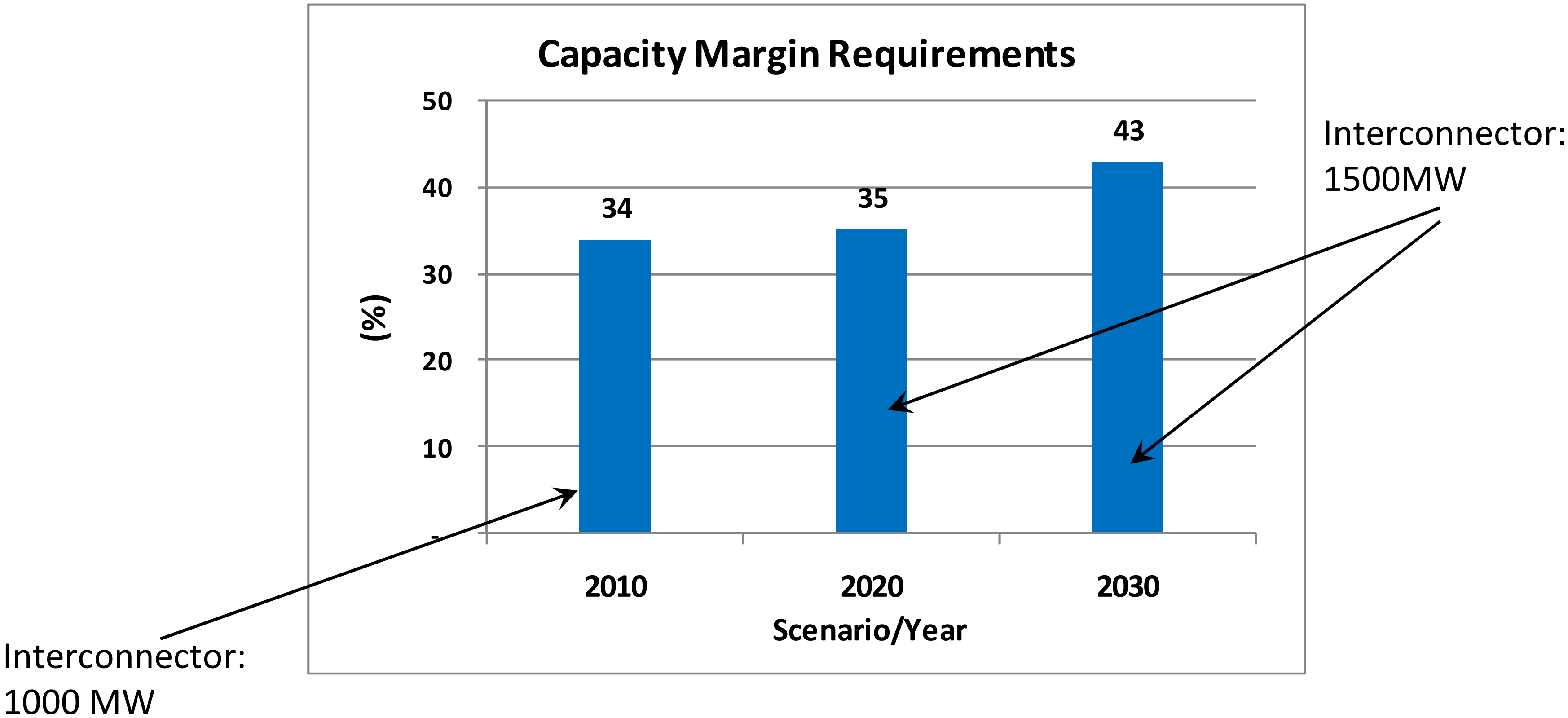
Capacity Modelling Approach – 2

- The unused capacity of the hydro reservoir type plant (i.e. the difference between installed capacity and dispatched power) during each simulation period (1/2-hour) is modelled as hydro capacity reserve to contribute to system reliability subject to reservoir energy constraints
- Main constraints include:
  - Aggregated (wind + Hydro + Thermal) production must meet demand in each time period
  - Minimization of wind and hydro energy curtailment
  - The aggregated reservoir size of each island for hydro energy storage
  - Minimum reservoir levels (10% of reservoir size)
  - 99% reliability of the interconnector (DC link between islands)

NZ Wind Farm (sites) Load Factors



System Capacity Margin Requirements



Key assumptions:

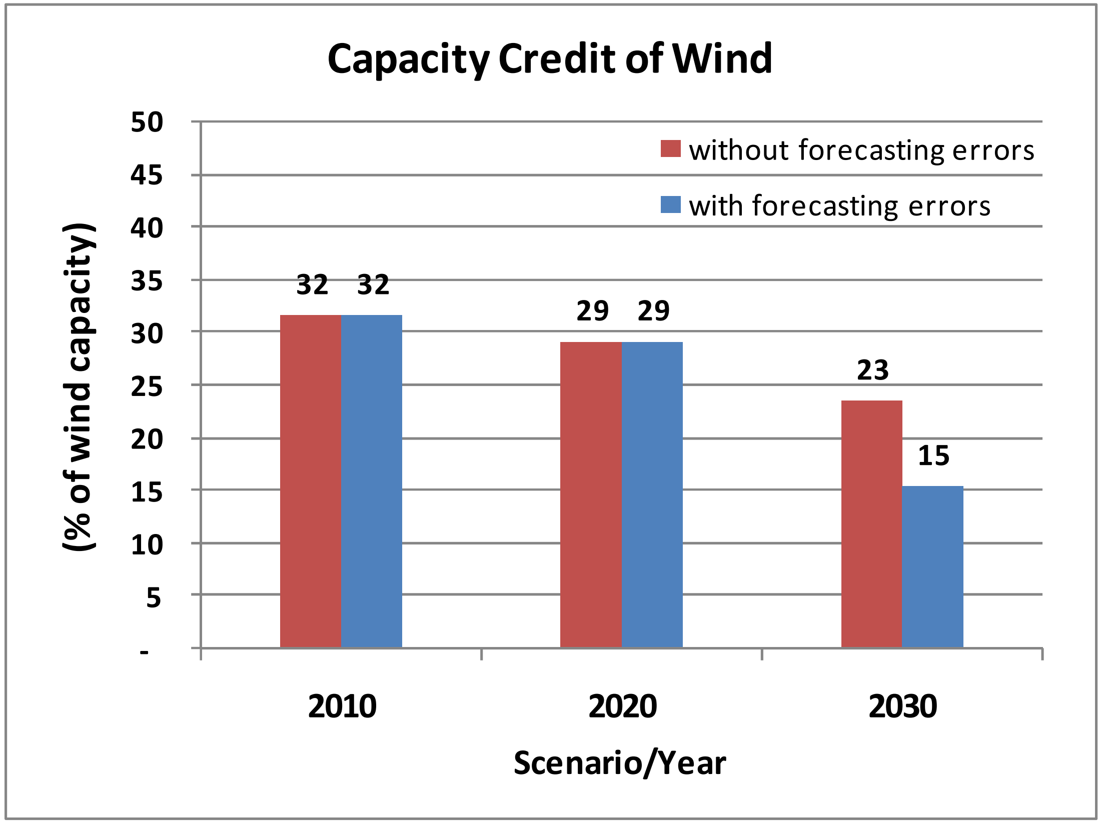
Conservative system reliability criterion: LOLE < 8 hours/year

Availability of conventional generation: 85% (consistent with planning time horizons)

NI-SI Interconnector reliability: 99%

Capacity Credit of Wind

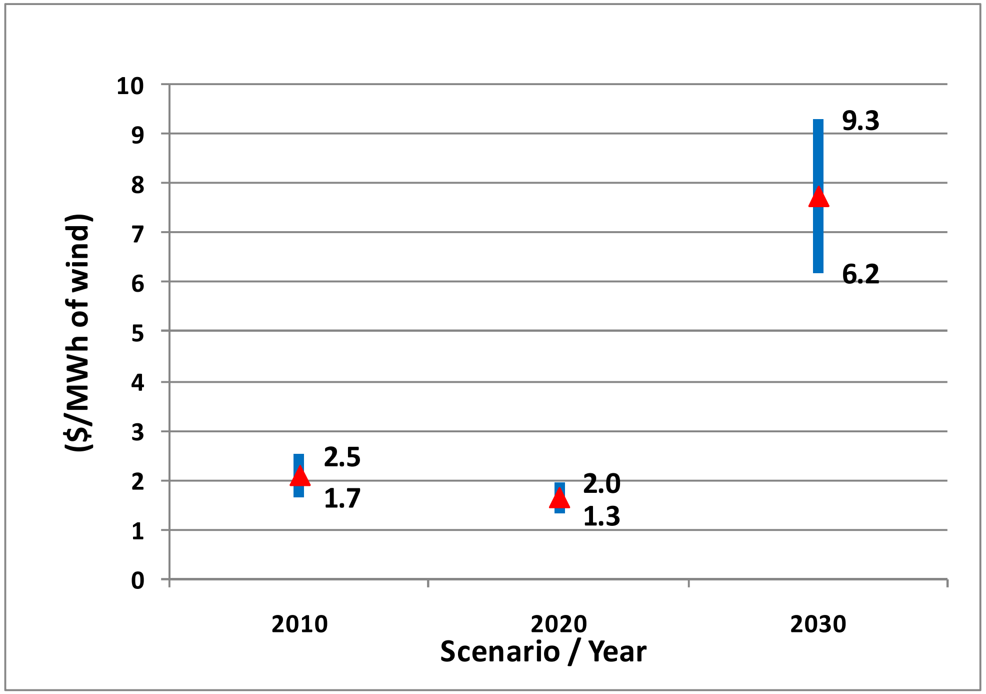
(Average hydro conditions)



Capacity credit with wind forecasting is based on a conservative approach to accommodate 99% of the wind variations across a 4 to 6 hour time horizon.

Additional Capacity Cost of Wind

(Average hydro conditions)



The source of additional capacity cost of wind generation is due to the difference between the quantites of energy versus capacity displaced when comparing wind power to a CCGT. The costs are driven by:

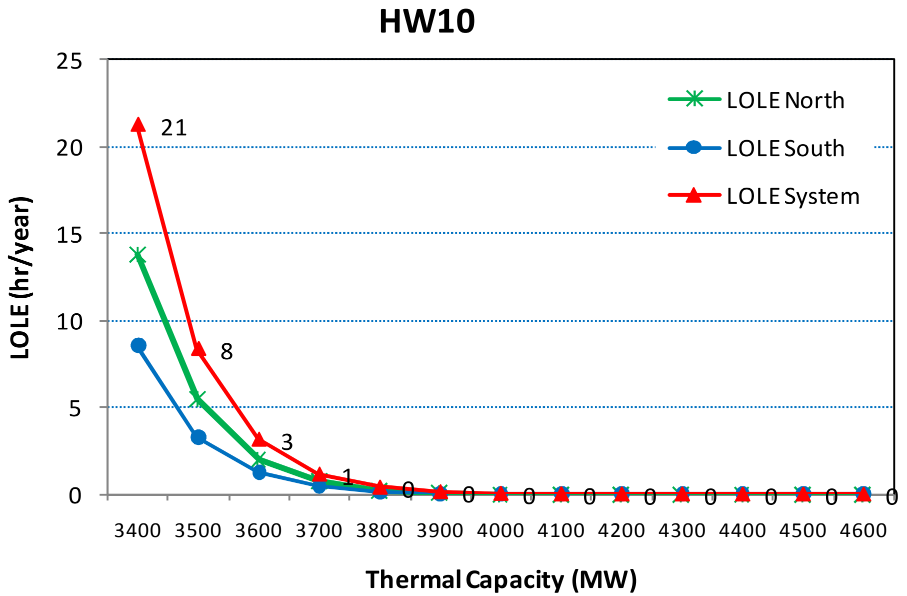
- Wind forecasting errors
- The utilisation of plant within the incumbent generation system
- The capacity of thermal plant required to be retained to maintain system reliability i.e., increased capacity margin

Assumptions:

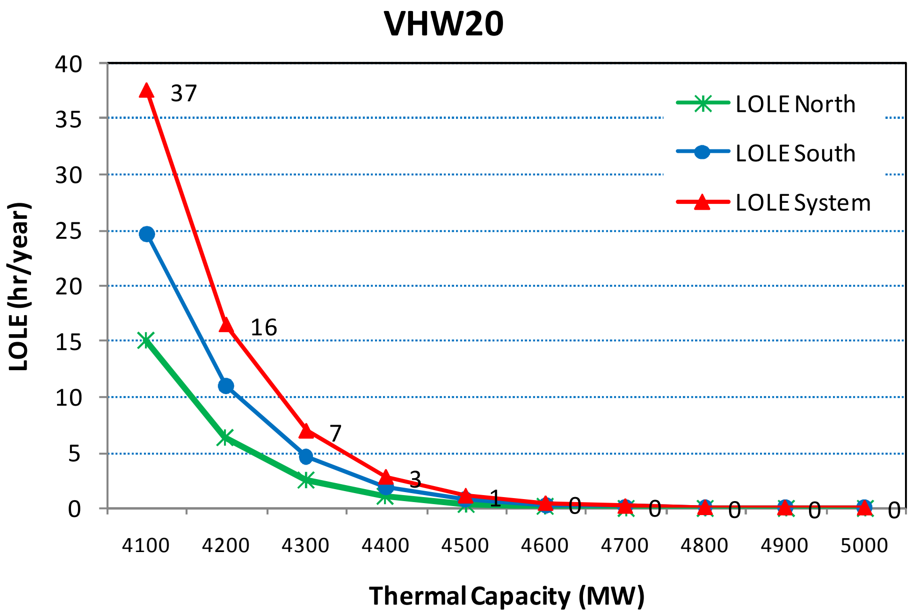
Capacity cost of conventional plant = 100 $/kW/yr to 150 $/kW/yr
Average load factor of thermal plant in the system = 58%
The additional costs of wind are relative to a base load thermal plant

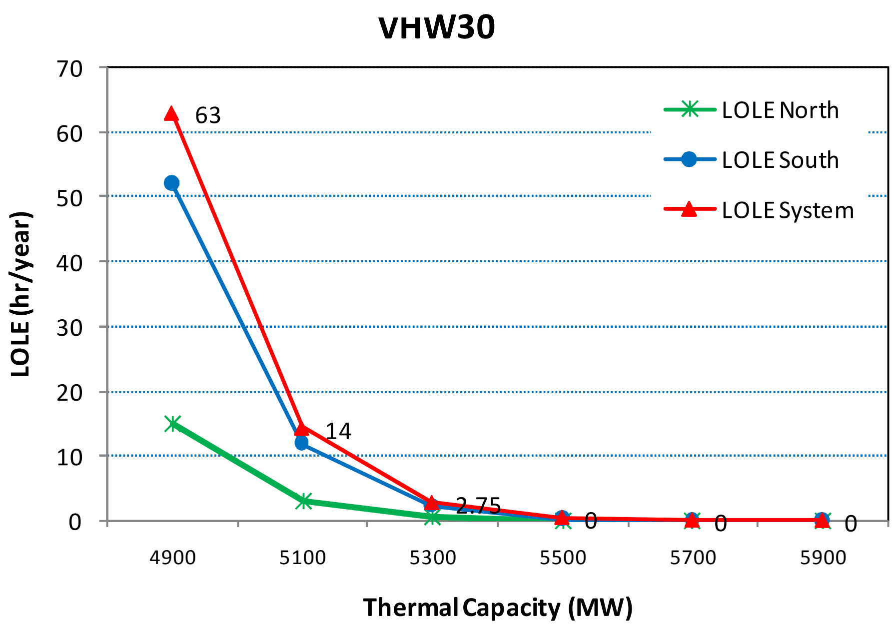
Changing role of the Interconnector

Interconnector: 520 MW



Thermal capacity is gradually added into the Island with higher LOLE or risk of non supply





Summary of Capacity Results - 1

- Unlike thermal generation based power systems in which capacity value of wind is determined by the availability of wind during peak demand conditions, the capacity value of wind in New Zealand is driven by its higher load factor as well as by the large variation in relatively small period of time
- Additional capacity costs attributed to wind generation:
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- Hydro increases capacity credit of wind - however at higher penetrations its contribution to firming up the wind power reduces
- Capacity credit of wind generation in the NZ's hydro dominated system is higher than in the other thermal based systems, however, it also declines with rise in wind penetration level
- Capacity values for wind are not effected by hydro (dry) conditions although the overall capacity requirements increase with low availability of hydro energy
- The low production of wind for days is found not to effect the capacity value of wind as this is compensated by the flexible hydro energy with presence of large hydro reservoirs
- The role of the interconnector changes over time – in 2010 South Island generation provides security of supply to the North Island – in 2020 and 2030 North Island generation provides security of supply to the South Island

Additional Costs of Reserve due to Wind Generation

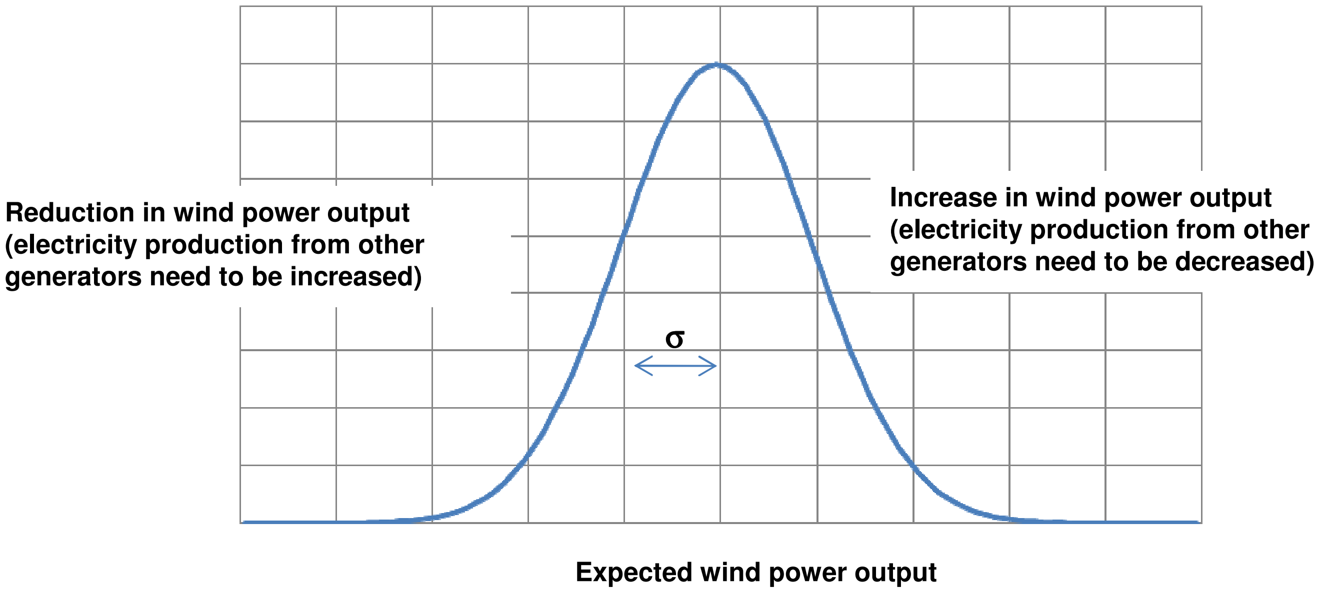
Methodology to Assess Additional Reserve Costs

1. Quantification of the additional operating reserve needed to deal with the forecasting errors of wind power
   A. Instantaneous reserve (up to 30 mins) provided by synchronised generators
   B. Frequency keeping reserve (up to 1 hour) provided by synchronised generators
   C. Scheduling reserve (for 4-6 hours) provided by synchronised and standing generators
2. Analysing the impact of increased reserve requirement on system operating costs
   A. Fuel cost, generation start up cost and no-load cost
   B. Cost of interruptible load
3. Evaluation of the cost of increased operating reserve requirements
4. Sensitivity analysis*
   A. Hydro conditions (Dry/Average/Wet)
   B. Increased wind power (scenario 2010,2020,2030)
   C. Interconnector capacity
   D. Location of future wind power (North and Southland scenarios)
   E. Different wind profiles (year 2005 and 2006 data based)

* **Sensitivity analysis are excluded from this executive summary**

Additional Reserve Assessment- Methodology

- Wind intermittency increases demand for operating reserve. Three types of reserves are modelled
  - Instantaneous reserve includes reserve to cover 30 minutes ahead wind unpredictability
  - Frequency keeping (1 hour ahead)
  - Scheduling reserve (4-6 hours ahead)
- The additional reserves due to wind are determined using a statistical analysis based on the distribution of wind forecasting errors



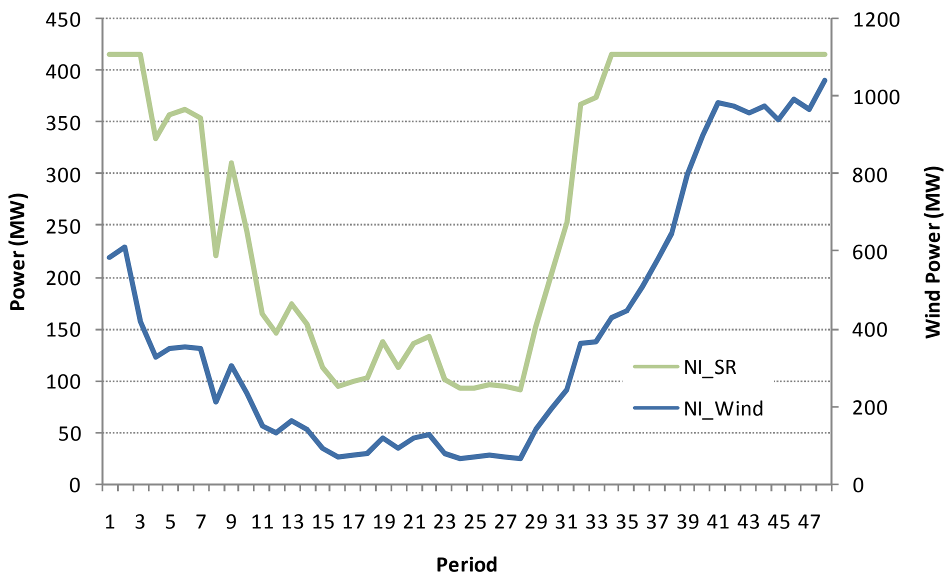
Note:
Sigma (σ) denotes the standard deviation. It is a measure of the spread of the values of wind power output from its mean μ (forecasted or expected value).
To cover 73% wind variability requires additional reserve (1σ).
96% → 2σ
99% → 3σ
99.5% → 4σ

Impact of Wind Variability on Reserves

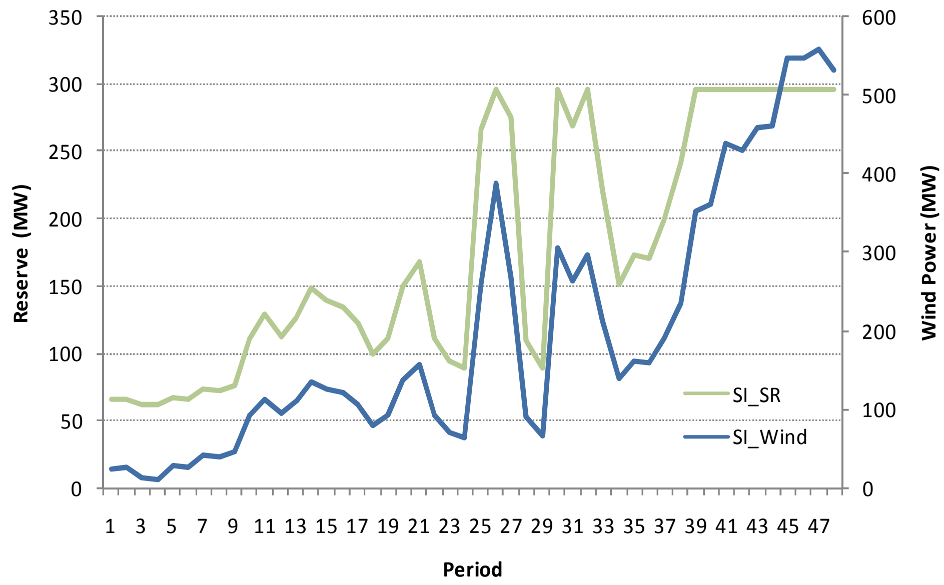
(Illustration)

(An illustrative winter peak demand day in 2020)

North Island



South Island



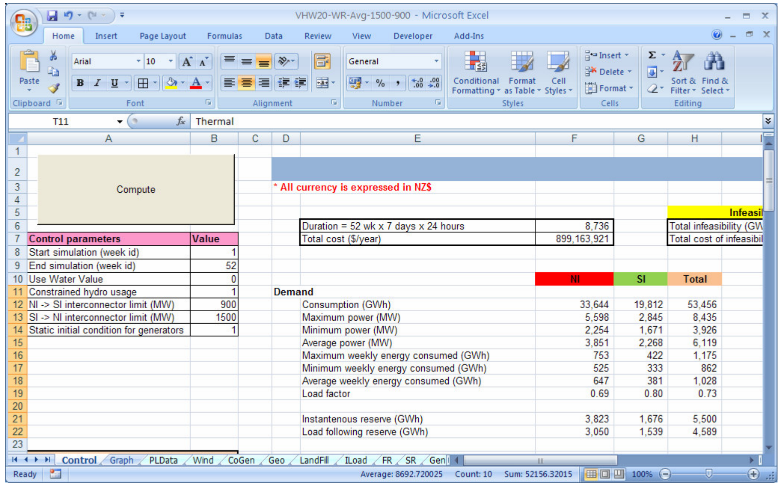
Amount of reserve required increases with increased wind output

Evaluation of Additional Reserve Costs

- Additional reserve will increase operating costs as wind power will demand
  - More on-line capacity
    - Use of low merit (expensive) generation
    - Lower efficiency- part loaded plants
  - Increased frequency of start ups of generators
  - Increased demand of Interruptible load (IL)
  - Increased standing reserve
- Cost of additional operating reserve attributed to wind is determined as the difference between the operating cost of the system with and without the wind reserve component
- Operating cost is determined using a generation scheduling optimisation model which optimises energy production and allocation of reserves among synchronised units
- Cost of standing reserve is determined by calculating the expected energy of standing reserve that would be exercised

The Optimisation Problem

- Objective
  - Minimise the overall generation cost including no load, start up cost and IL cost subject to operational constraints
- Include operational constraints
  - Power balance constraints
  - Generation constraints
    - Minimum stable generation
    - Power rating
    - Maximum Instantaneous Reserve limits
    - Ramp up/down constraints
    - Minimum up/down time constraints
    - Load factor constraints for CCGT (minimum 75%)
  - 0.5 hourly auxiliary and wind power energy constraints
  - Hydro power constraints
    - Daily ROR energy constraints
    - Weekly hydro inflows constraints
    - Reservoir constraints
  - Reserve constraints
    - Minimum instantaneous and frequency keeping reserve provision for each island
  - Flow constraints at interconnector
- Use of mixed integer linear programming



Reserve Modelling Assumptions - 1

- Additional operating reserves in each Island is analysed separately, i.e. no operating reserve transfers across the HVDC link are modelled
- The magnitude of power transfers across HVDC link is constrained by power transfer capability constraint. The maximum of NI to SI transfer is set to 60% of SI to NI power transfer
- All operating spinning reserve quantities for instantaneous reserve and frequency keeping are assumed to be unable to contribute to meeting demand requirements
- Operating reserve is assumed to be mainly provided by part loaded plant along with a contribution from demand side (interruptible load) during critical periods, consistent with existing practices
- Standing reserve is assumed to be provided by off-line thermal plants which can synchronise and produce electricity quickly to maintain balance between supply and demand
- Levels of operating reserve required are targeted to cover about 99.5% of all operating conditions

Reserve Modelling Assumptions - 2

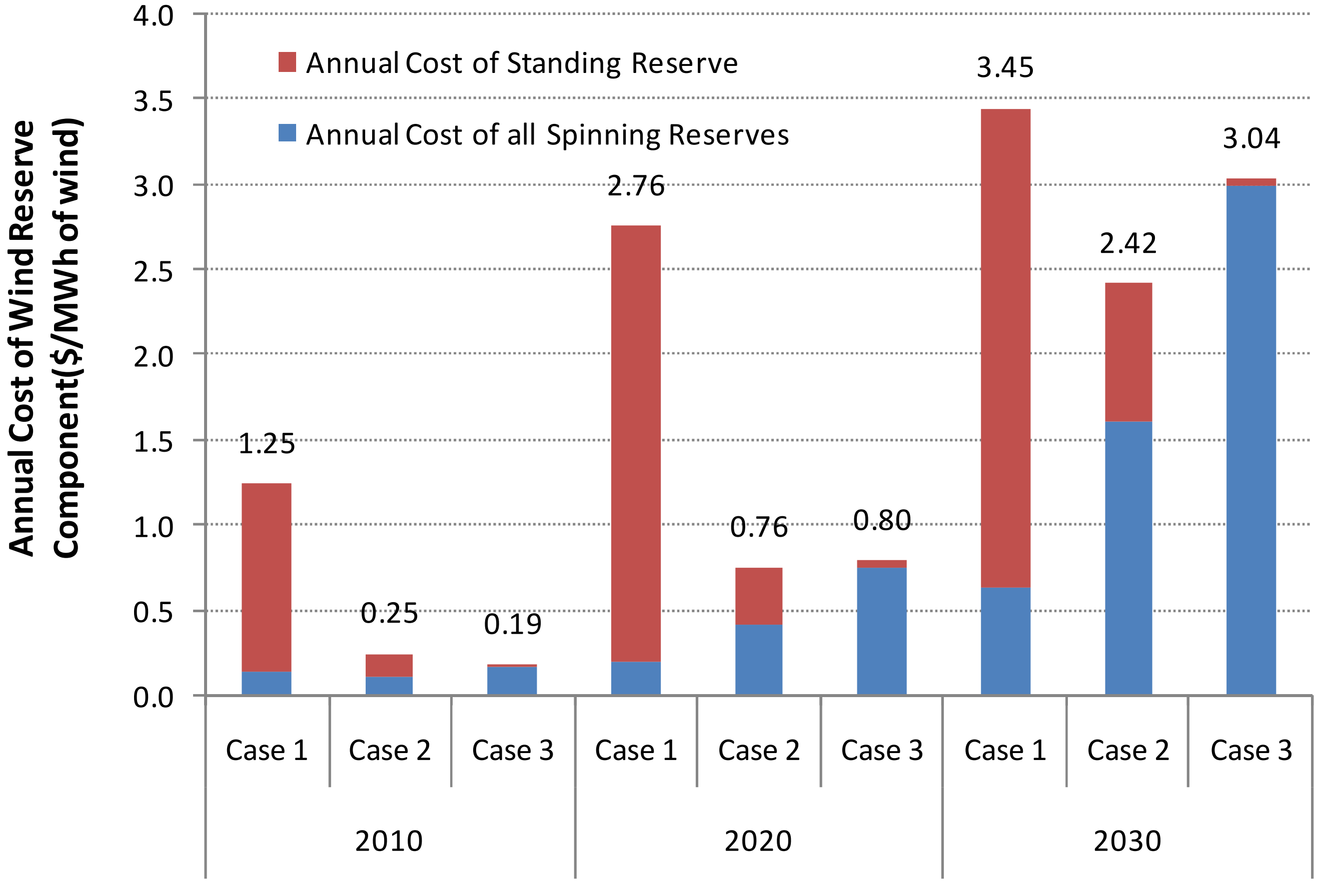
- Reserve requirements from synchronised plant are assessed at 30 minutes and 1 hour. Standing reserve are allocated for dealing with the forecasting errors beyond 1 hours
- Reserve requirements are computed for each half hour time slot of the overall system simulation.
- The additional reserve requirement to deal with wind variability never exceeds expected wind power output.
- In the daily load cycles, the impact of different loading conditions during day and night periods on the operating reserve requirements is modelled.
- CCGT was assumed to operate with minimum load factor of 75% irrespective of hydro and wind conditions.

Required Quantities of Operating Reserves

		2010			2020			2030		
		IR	FK	Standing	IR	FK	Standing	IR	FK	Standing
Case 1	NI	398	107	124	446	215	312	533	315	503
	SI	167	73	65	245	157	174	379	271	326
	NZ	565	180	189	691	372	486	912	586	829
Case 2	NI	398	150	81	446	314	272	533	466	352
	SI	167	93	31	245	226	105	379	400	214
	NZ	565	243	112	691	540	377	912	866	566
Case 3	NI	398	194	37	446	416	170	533	618	200
	SI	167	115	9	245	296	35	379	530	67
	NZ	565	309	46	691	712	205	912	1148	267

Note: all units are expressed in MW
IR = Instantaneous Reserve
FK = Frequency Keeping

Optimal Allocation of Standing and Spinning Reserves



Case1: dominated by standing reserve

Case2: balanced allocation

Case3: dominated by spinning reserve

Summary of the Reserves Results

- Additional reserves are needed to cover the unpredictability of wind power
  - Instantaneous reserve provided by synchronised generators
  - Frequency keeping reserve to cover 1 h wind variability provided by synchronised reserve
  - Scheduled reserve to cover 4-6 h wind variability provided by synchronised + standing reserve
- The quantity of wind reserve component increases with rise in wind penetration
- Provision of scheduling reserve up to 4-6 h time horizon
  - For low wind penetration (2010), hydro will be the primary source
  - For high wind penetration (2020 &2030), it is desirable to use flexible standing power plants
- The cost of additional reserve to deal with forecasting error of wind for several scenarios have been quantified
  - For low penetration (4.9% in 2010) , it is around 0.19 $/MWh of wind energy
  - It increases to 2.42 $/MWh of wind energy in 2030 with high wind penetration (17.9%)
- The primary source of synchronized reserve remains to be hydro but in future, it will require higher contribution from IL and other thermal plants

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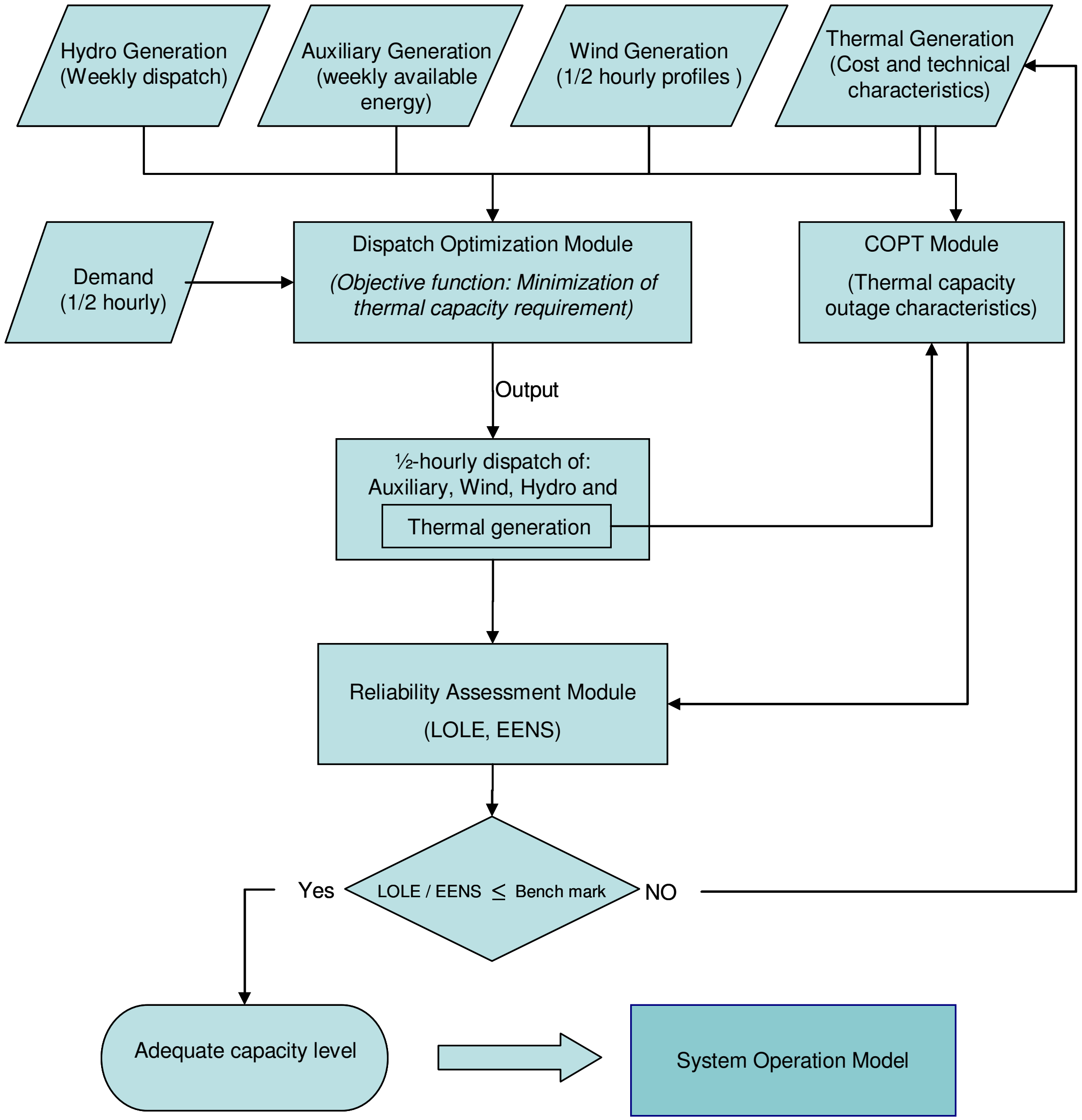
Appendix

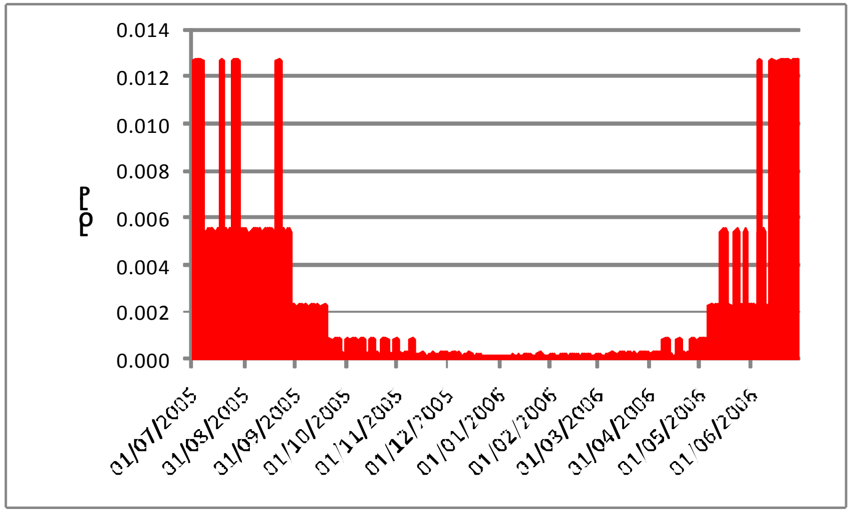
Simplified Representation of the Capacity Adequacy Assessment Model

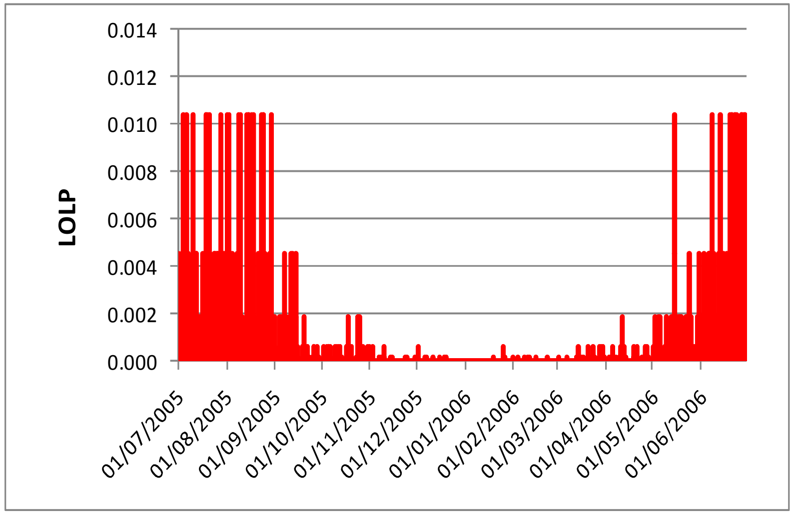


Yearly Distribution of Loss of Load Probability

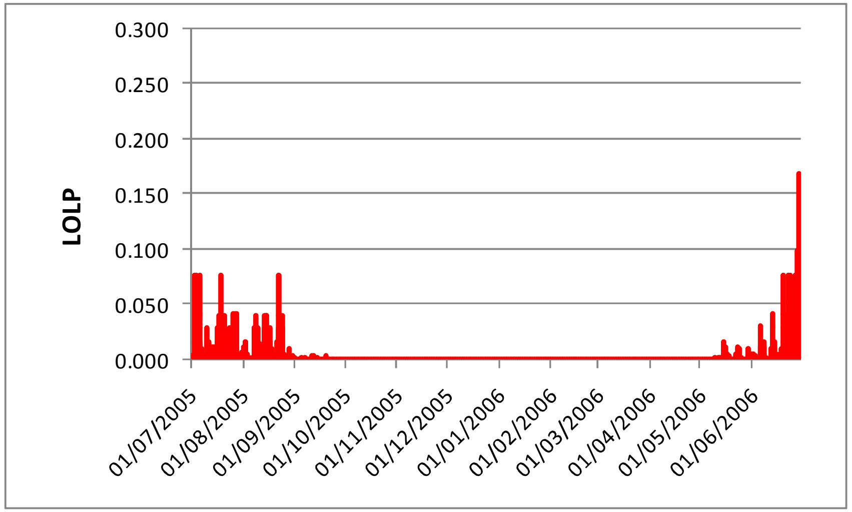
Without Wind | **With Wind**

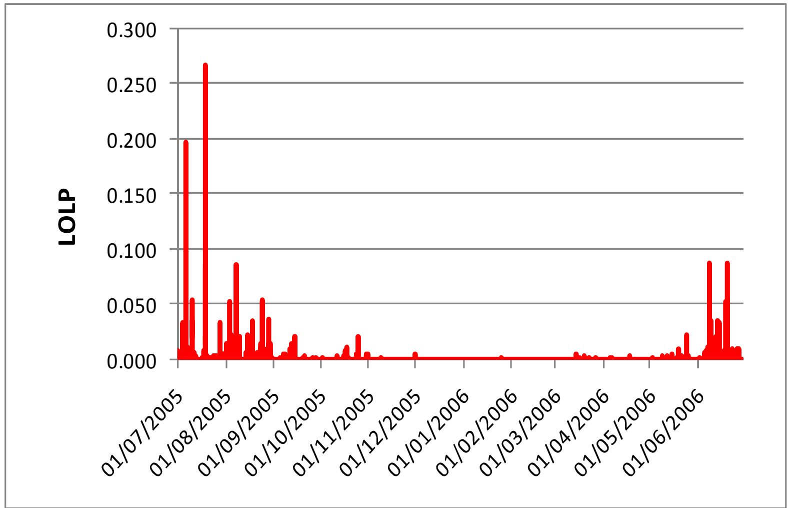
2010





2030



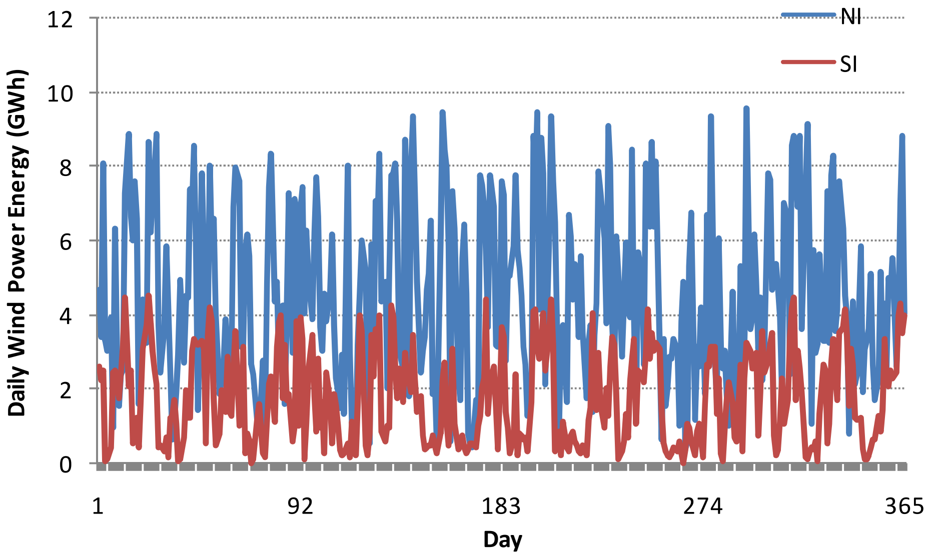


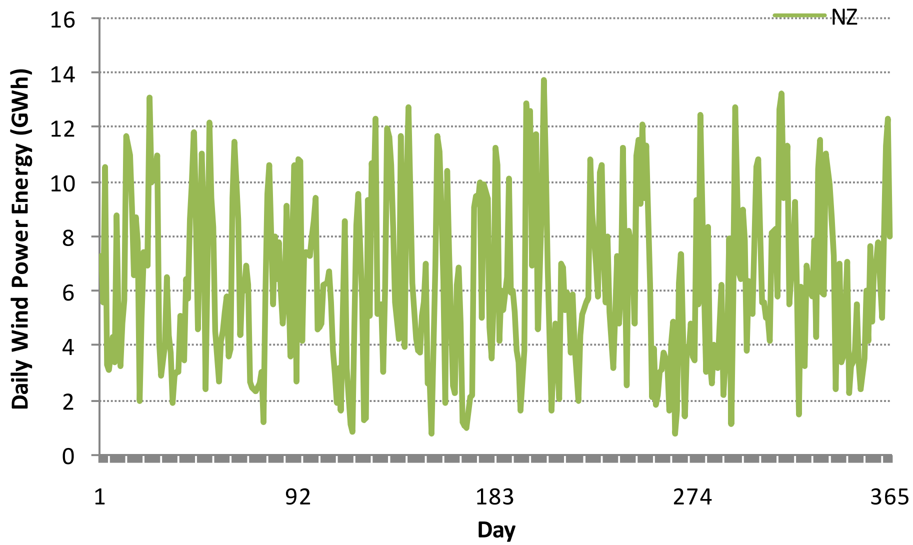
Initial Electricity Generation & Demand Scenarios

Scenario	High Wind 2010(4.9%)			Very High Wind 2020 (12.5%)			Very High Wind 2030 (17.9%)		
Region >>	NI	SI	NZ	NI	SI	NZ	NI	SI	NZ
Auxiliary	1,017	37	1,054	1,166	37	1,203	1,205	37	1,242
Wind	432	203	634	1,434	632	2,066	2,215	1,197	3,412
Hydro	1,873	3,557	5,430	1,873	3,557	5,430	1,873	3,557	5,430
Coal	972	-	972	972	-	972	972	-	972
Gas	1,500	-	1,500	1,570	-	1,570	1,810	-	1,810
Oil	-	-	-	-	-	-	-	-	-
Distillate	156	-	156	156	-	156	156	-	156
Total installed generation capacity (MW)	5,949	3,797	9,747	7,171	4,226	11,397	8,230	4,791	13,022
Hydro energy (GWh)	6,919	17,929	24,848	6,919	17,929	24,848	6,919	17,929	24,848
Wind energy (GWh)	1,653	631	2,285	4,906	1,819	6,724	7,442	3,354	10,797
Peak demand (MW)	4,842	2,455	7,297	5,598	2,845	8,443	6,273	3,197	9,469
Energy demand (GWh)	28,952	17,041	45,993	33,644	19,812	53,456	37,907	22,351	60,258

Wind Profiles

Based on 2005 wind profiles for 2010 scenario



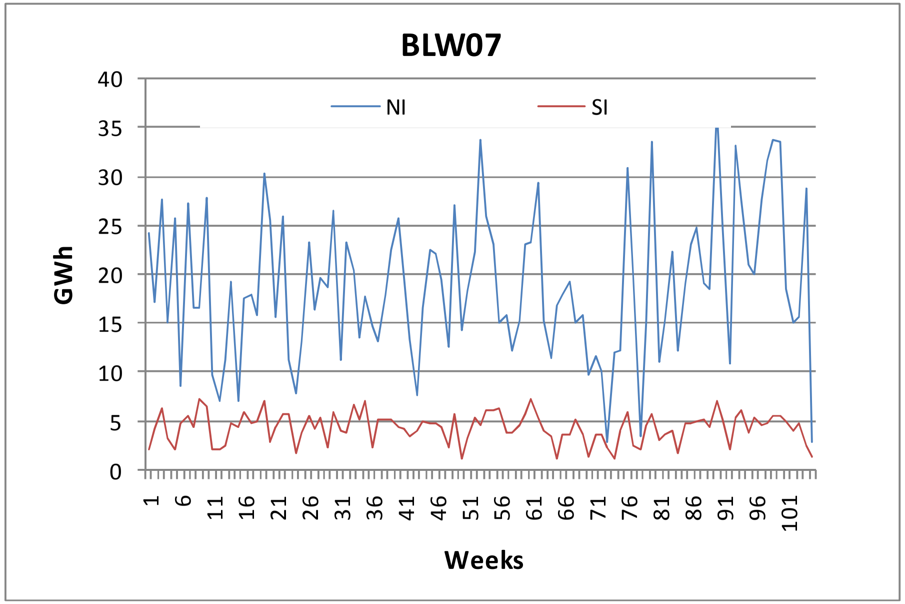


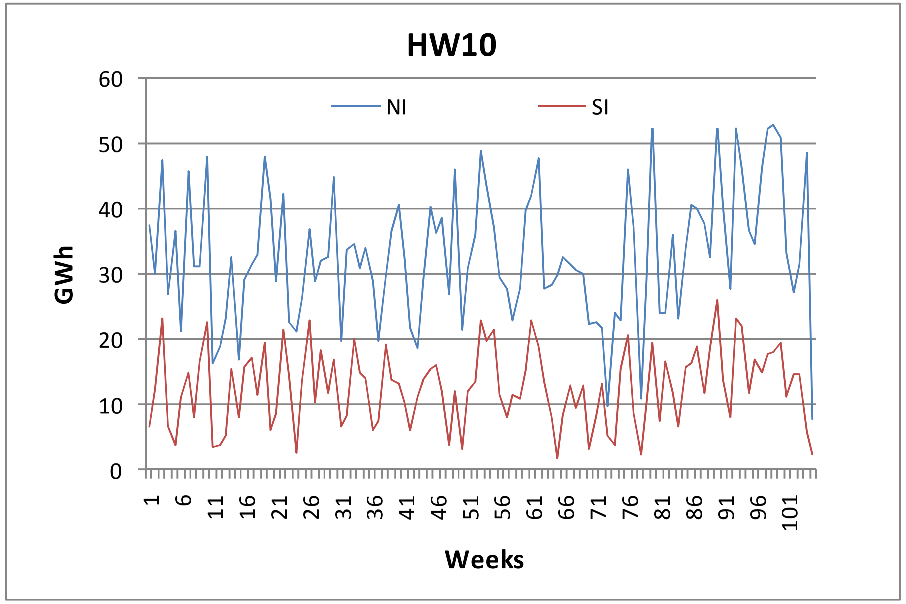
Wind energy (GWh)	NI	SI	Total
Annual	1,653	631	2,285
Weekly maximum	49	24	72
Weekly minimum	15	2	20
Weekly average	32	12	44

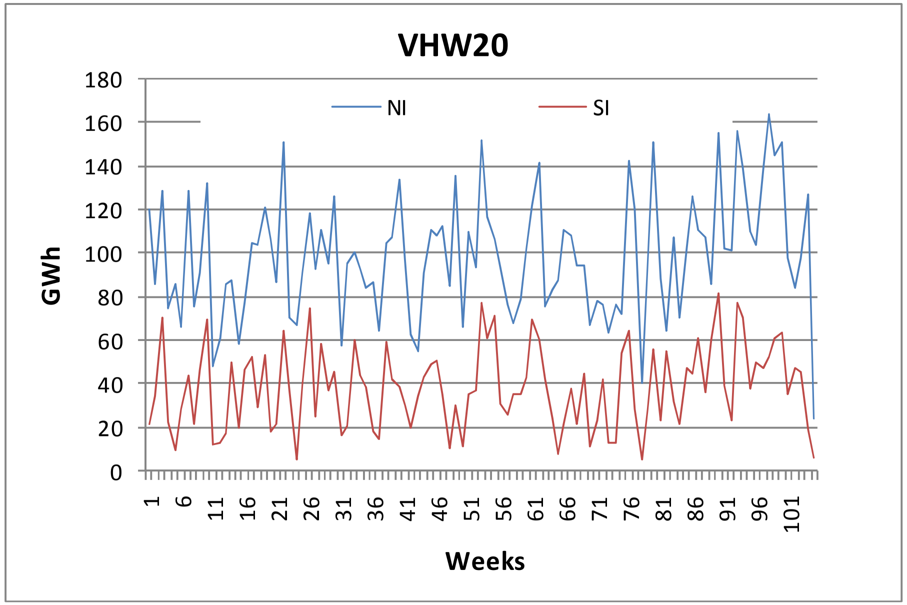
Wind energy (GWh)	NI	SI	Total
Annual	4,906	1,819	6,724
Weekly maximum	145	72	199
Weekly minimum	47	5	57
Weekly average	94	35	129

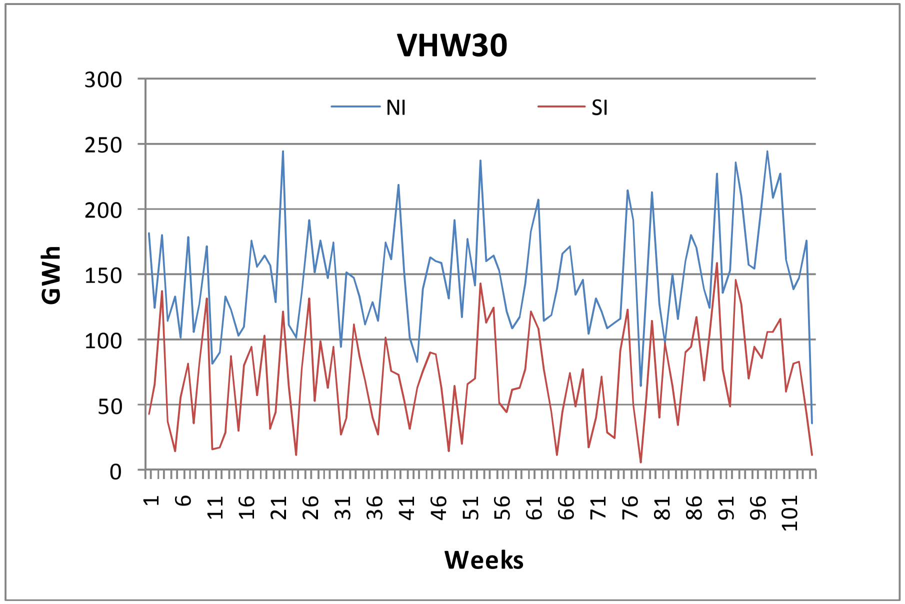
Wind energy (GWh)	NI	SI	Total
Annual	7,442	3,354	10,797
Weekly maximum	228	140	320
Weekly minimum	77	8	94
Weekly average	143	65	208

Weekly Wind Production

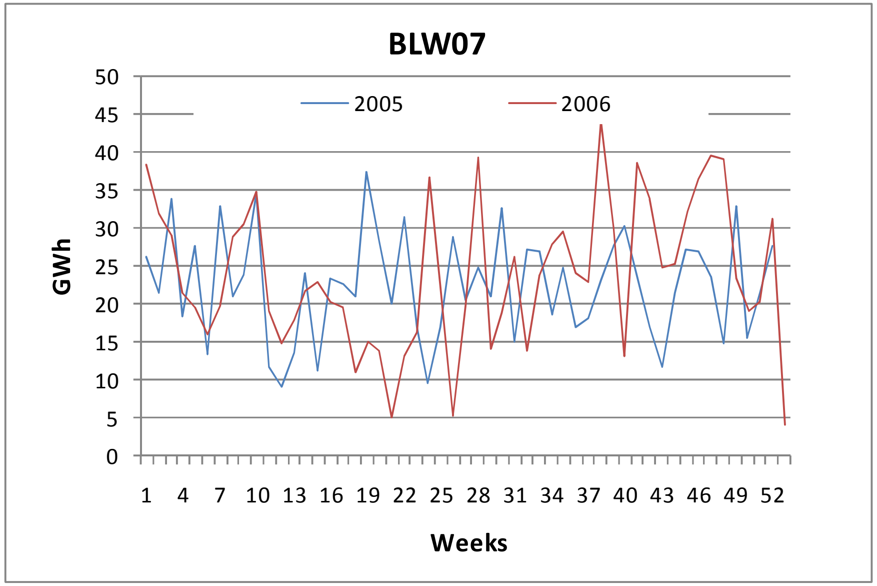


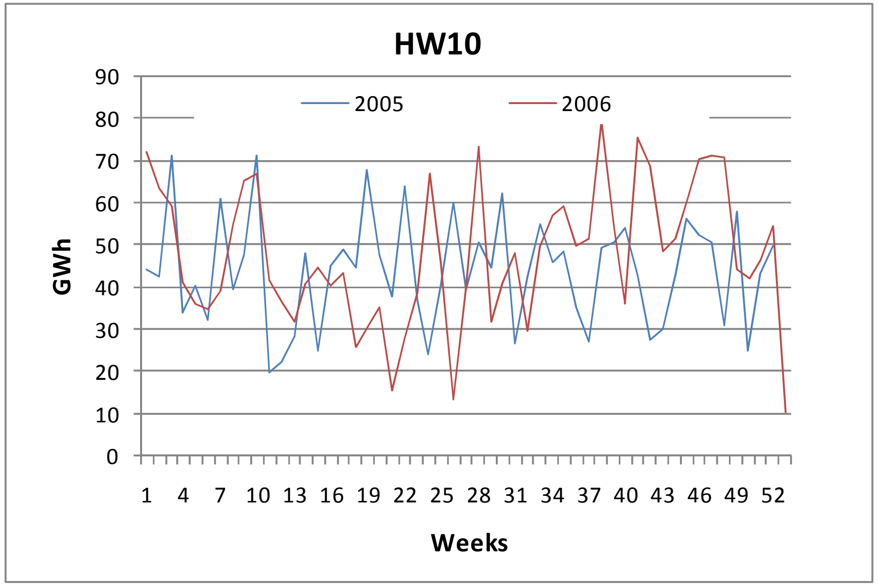


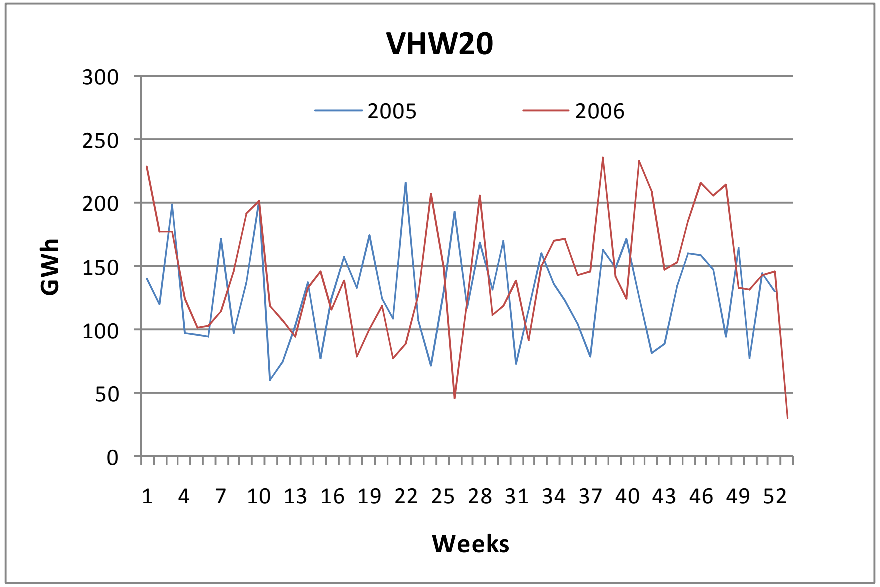


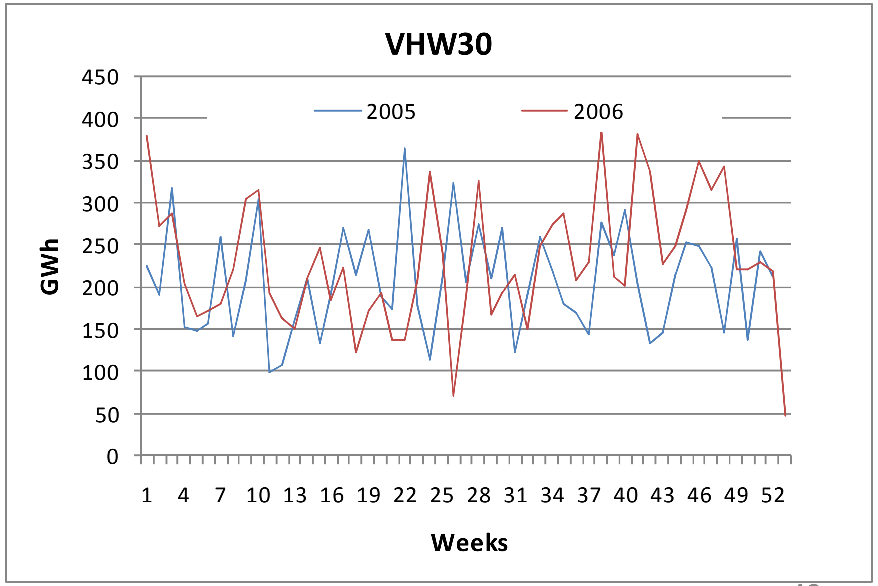


Weekly Wind Production (across years)





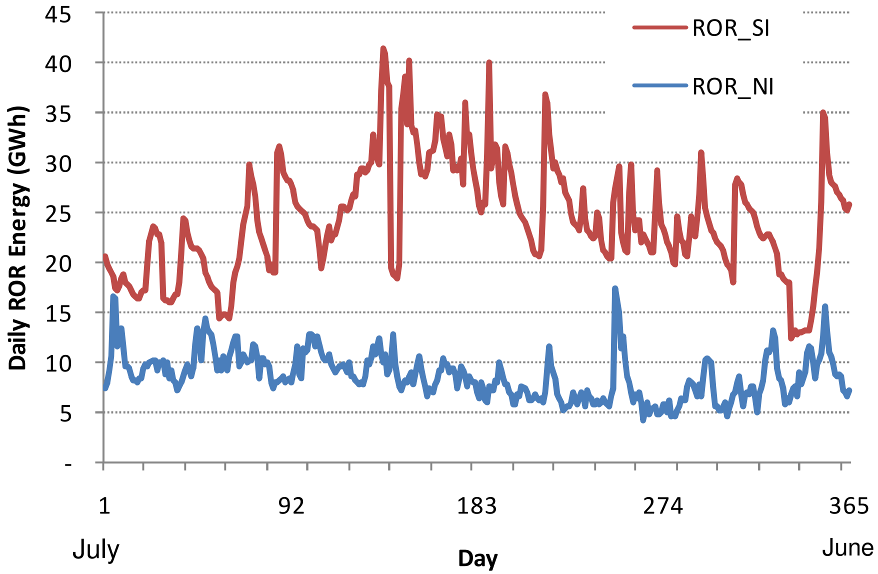


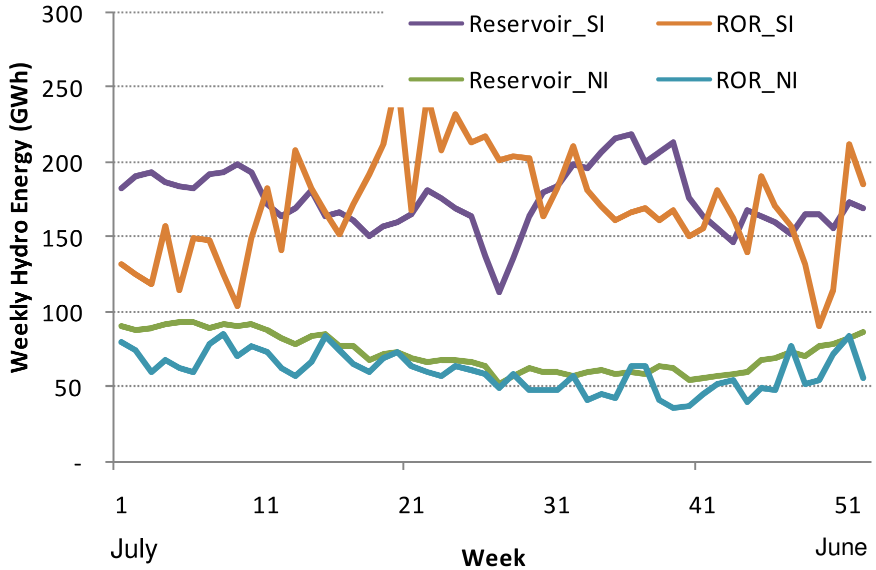


Data starts from first week of January

Hydro Profiles

Based on average hydro condition

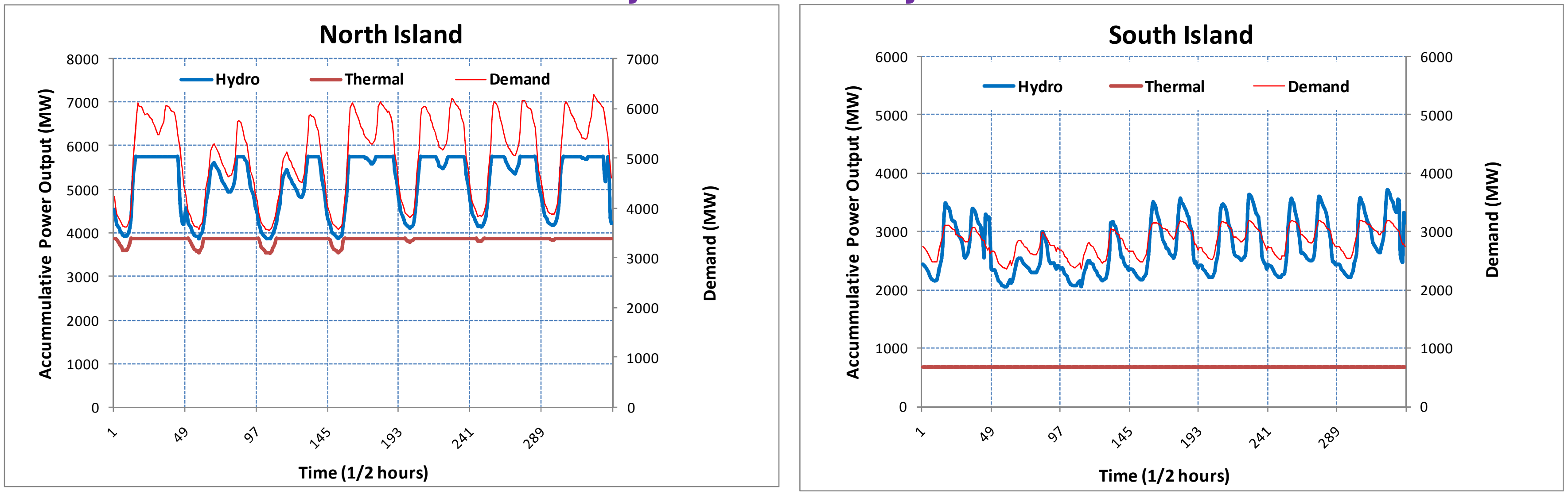




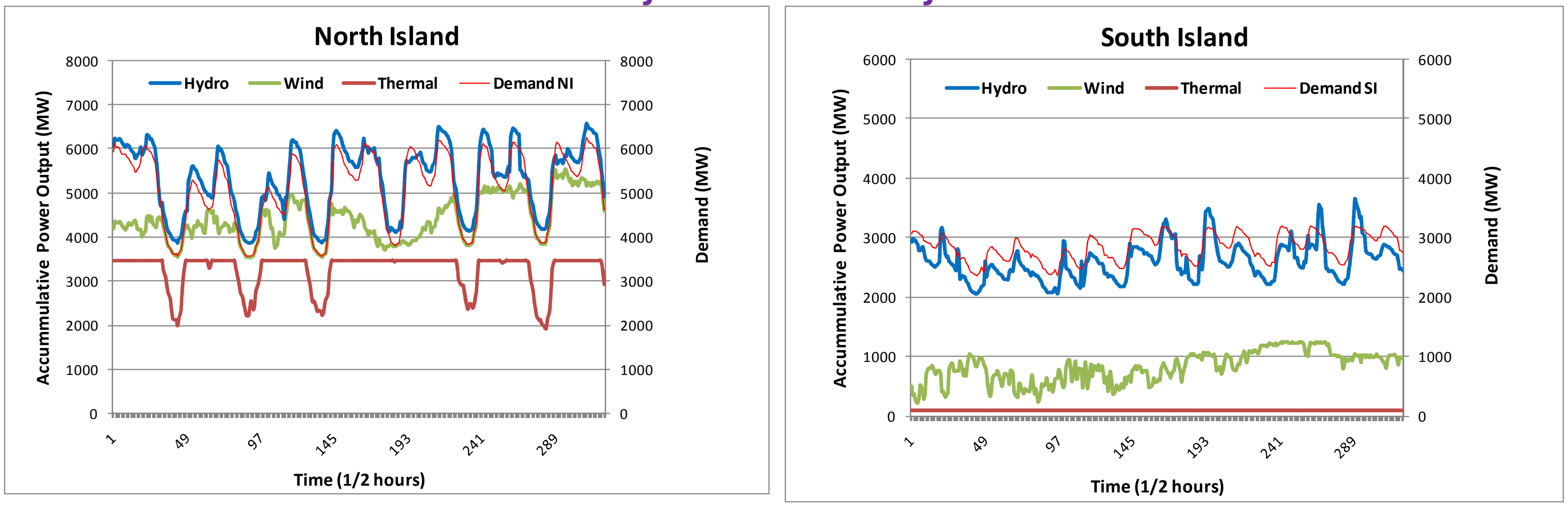
	Reservoir			Run of River			Total		
	NI	SI	NZ	NI	SI	NZ	NI	SI	NZ
Total energy (GWh)	3,760	9,080	12,840	3,159	8,849	12,008	6,919	17,929	24,848
Weekly maximum (GWh)	93	219	289.0	86	256	330	178	474	619
Weekly minimum (GWh)	52	113	165.3	36	90	145	89	203	310
Weekly average (GWh)	72	175	246.9	61	170	231	133	345	478

Illustrative one week dispatch -2030 Scenario
Hydro tends to flatten output of thermal generation

Hydro-Thermal System

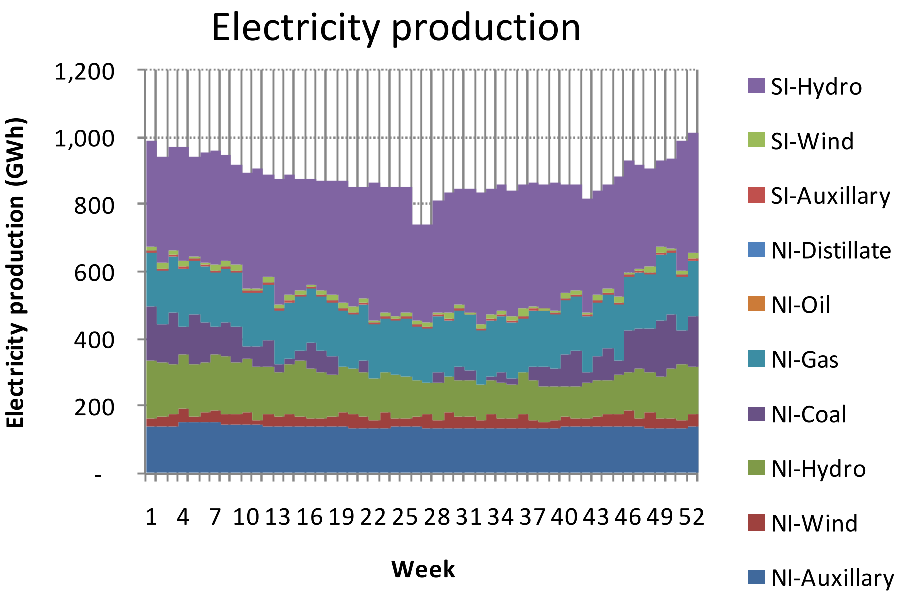


Wind-Hydro-Thermal System



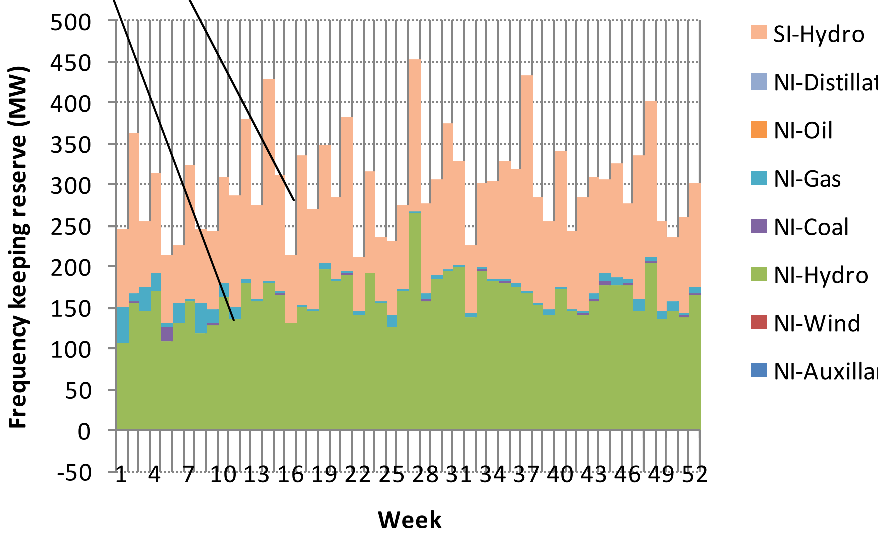
Providers of Reserves - Low Wind Penetration

High Wind Scenario 2010

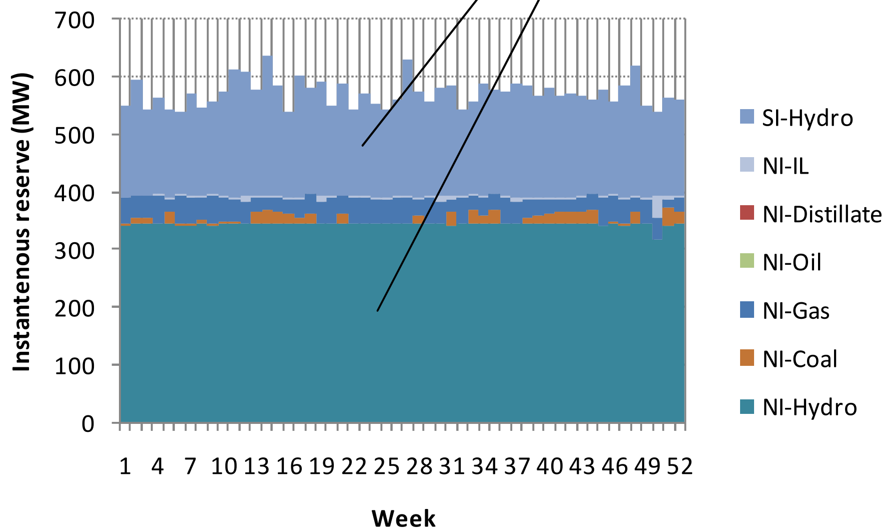


Throughout the year, hydro is primary source for FK

Primary source of Primary source for instantaneous reserve is Hydro (not affected by demand)



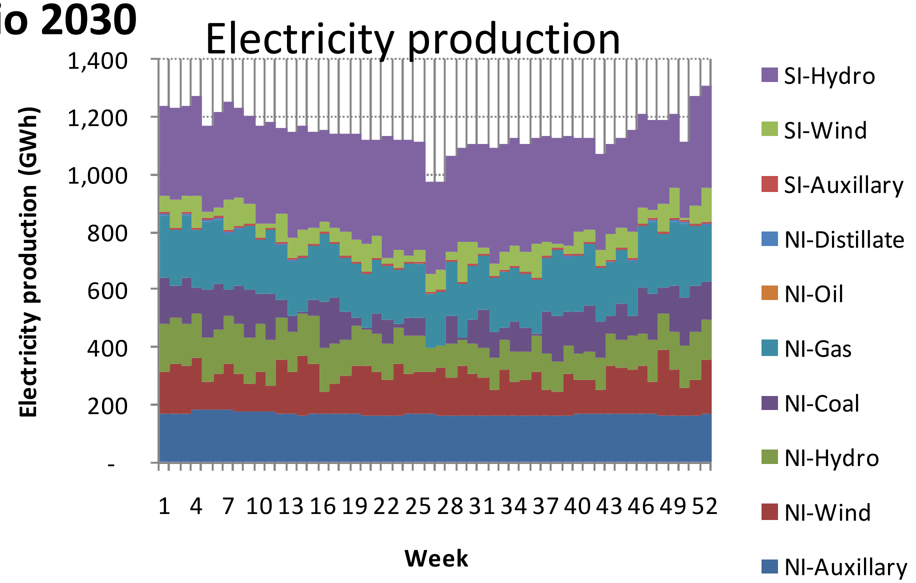
Frequency Keeping Reserve



Instantaneous Reserve

Providers of Reserves - High Wind Penetration

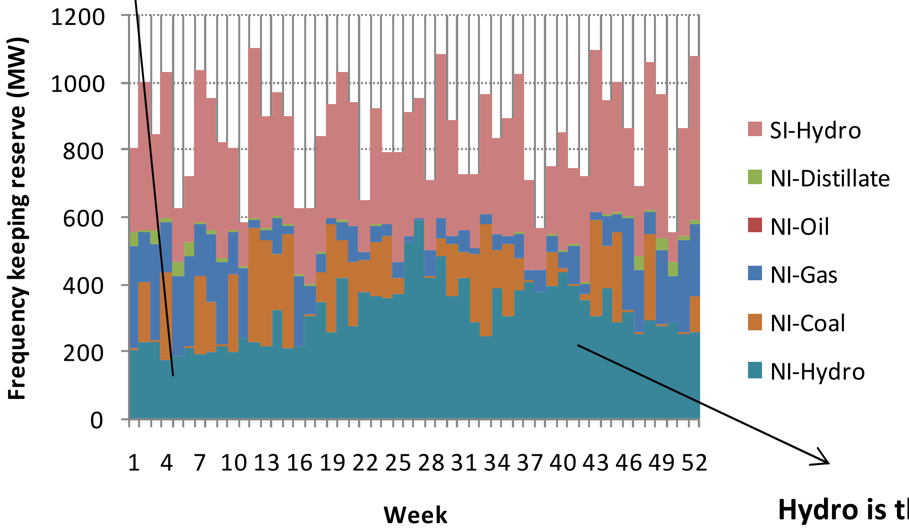
Very High Wind Scenario 2030



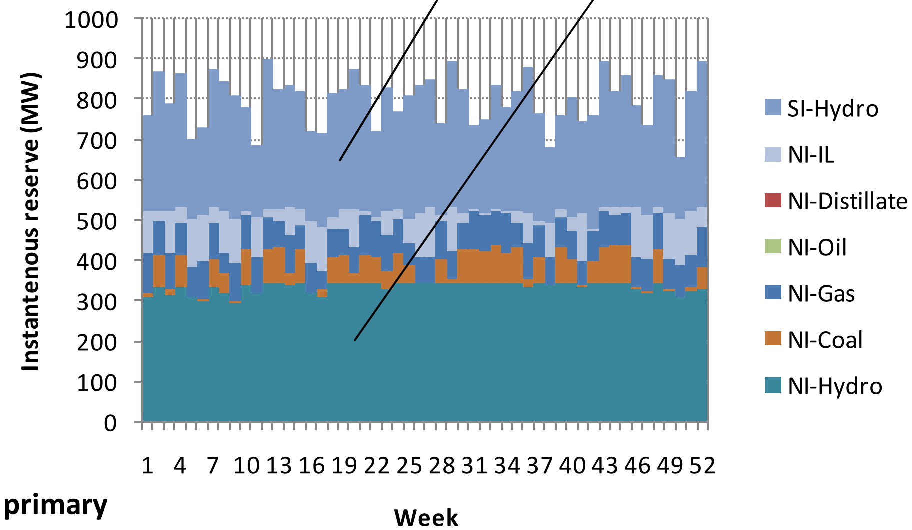
Primary source of instantaneous reserve is Hydro (not affected by demand)

Coal, Gas and IL contribute to the provision of IR

FK reserve from Hydro is less during peak demand (hydro provides more energy)



Frequency Keeping Reserve



Instantaneous Reserve

Hydro is the primary source for FK during off peak demand