Wind energy

Energy Centre summer school in Energy Economics
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Outline

• The technology

• Wind energy in the world

• Wind research at the Energy Centre
The technology
Wind power calculation

\[ P_{\text{wind}} = \frac{1}{2} \rho A v^3 \]

\[ A = \pi \left( \frac{D}{2} \right)^2 \]

- Effect of air density, \( \rho \) (kg/m\(^3\))
- Effect of swept area, \( A \) (m\(^2\))
- Effect of wind speed, \( v \) (m/s)
Wind turbine power curve

![Wind turbine power curve diagram](image)
Capacity factor

\[ cf = \frac{\text{the total amount of energy produced during a period of time}}{\text{the amount of energy produced at full capacity}} \]

\[ cf = \frac{\text{actual energy generated (MWh)}}{\text{capacity (MW)} \times \text{time period (h)}} \]
# Wind resource in New Zealand

<table>
<thead>
<tr>
<th>Year</th>
<th>Installed capacity (MW)</th>
<th>Generation (GWh)</th>
<th>Capacity factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>690</td>
<td>1860</td>
<td>?</td>
</tr>
<tr>
<td>2019</td>
<td>690</td>
<td>1829</td>
<td>?</td>
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<tr>
<td>2018</td>
<td>689</td>
<td>1659</td>
<td>?</td>
</tr>
<tr>
<td>2017</td>
<td>689</td>
<td>1678</td>
<td>?</td>
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<tr>
<td>2016</td>
<td>690</td>
<td>1904</td>
<td>?</td>
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<tr>
<td>2015</td>
<td>689</td>
<td>1914</td>
<td>?</td>
</tr>
<tr>
<td>2014</td>
<td>682</td>
<td>1946</td>
<td>?</td>
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<tr>
<td>2013</td>
<td>621</td>
<td>1865</td>
<td>?</td>
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\text{cf} = \frac{\text{actual energy generated (MWh)}}{\text{capacity (MW) } \times \text{ time period (h)}}
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## Wind resource in New Zealand

### Table

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<td>30.8%</td>
</tr>
<tr>
<td>2019</td>
<td>690</td>
<td>1829</td>
<td>30.3%</td>
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<tr>
<td>2018</td>
<td>689</td>
<td>1659</td>
<td>27.5%</td>
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<td>2017</td>
<td>689</td>
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<td>27.8%</td>
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<td>2015</td>
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<td>1914</td>
<td>31.7%</td>
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<td>682</td>
<td>1946</td>
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<td>33.5%</td>
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</table>

### Formula

$$ cf = \frac{\text{actual energy generated (MWh)}}{\text{capacity (MW)} \times \text{time period (h)}} $$

For example: capacity factor_{2011} = (1824*1000)/(621*365*24) = 0.335

Wind resource in New Zealand
Hourly Average Wind Speed 2005-2007

Self-elaboration. Date source: NIWA (Jan 2005 to Dec 2007)
Wind energy in the world
**Historical milestones I**

**Middle Ages**
- Iran (by 7th to 9th century): grinding corn and pumping water
- Middle East, Central Asia, China, India, Sicily (by 1000 AD): seawater pumping for making salt
- North-western Europe (1180s on): grinding flour

**19th century**
- Denmark, by 1900: 2500 windmills (30 MW) for mechanical loads such as pumps, and mills.
- American Midwest, 1850-1900: 6 million small windmills for irrigation
- Scotland, 1887: Prof James Blyth built the first windmill for production on electricity, used for providing lighting in his holiday cottage
- Ohio, 1888: Charles F. Brush’s 17m rotor diameter, 144 blades, wind turbine, 12 kW, used to charge batteries or operate up to 100 (inefficient!) light bulbs
Historical milestones II

20th century

- 1901-1973: wind generators widespread, but competed against fossil fuel plants and centrally generated electricity
  - USSR, 1931: 100kW, 30m diameter (d)
  - UK, early 1950s: 100kW, 24m (d)
  - Denmark, 1956: 200kW, 24m (d)
  - France, 1963: 1.1MW, 35m (d)
- 1973-onwards: oil price crisis spurred investigation of non-petroleum energy sources
  - USA, 1980s: Total US installed wind power capacity is 10MW, for 8,575 homes.
  - USA, 1981: 3MW horizontal axis, hydraulic transmission instead of yaw drive
  - USA, 1987: 3.2MW, the first large-scale variable speed drive train and a two-blade rotor.
  - Canada, 1984: 4MW Darrieus wind turbine
  - Large turbines constructed with 1, 2 or 3 blades (prototypes)
  - Smaller, often simpler turbines available for commercial sale
Modern wind turbines

The Danish concept:
• 3-bladed, stall-regulated rotor, fixed speed became dominant model in 1980s, less than 200kW rated power

More recent developments:
• 2-3MW(3-8MW)/97-117m(112-164m) diameter onshore (offshore)
• Rotor speed: Fixed speed / Variable speed
• Blade control: Full-span control of the blades (pitch regulated)
• Advanced materials: blades lighter -> can be made longer
• Drive train: Direct-drive concept vs. gearbox + high speed generator
World’s largest wind farms (onshore)

• The Gansu Wind Farm Project
  ➢ Jiuquan base
  ➢ The first phase of the wind farm with 5.16GW, 3500 turbines was completed in Nov 2010.

• Current capacity - 10 GW; Planned -20GW.

• 7000 wind turbines

• Cost US$15billion
Offshore technologies

• Existing foundation types
  - Monopoles (a single cylindrical structure—e.g. the London Array)
  - Jackets (a series of cylindrical tubes—e.g. the Alpha Ventus wind farm located off the coast of Germany)

• Emerging foundation solutions
  - Floating foundations
    — tension-leg-platforms
    — semi-submersible
    — spar buoys

• Main issues for offshore wind power
  - Going deeper, farther from coast – foundations & interconnections
  - Reliability – high cost of maintenance!
  - Need for mainstreaming installation processes (currently few specialised vessels)
World’s largest wind farms (offshore)

Hornsea 2 (1.32GW) -2021

- The largest offshore wind farm in the world
- In the North Sea off the coast of England
- 165 8MW Siemens Gamesa wind turbines
- Together with sibling Hornsea 1 (174 Siemens SWT-7.0-154, 1,218MW) can power 2.3 million homes
- Current capacity – 3.5 GW; Planned -6GW.
Hywind Scotland: world’s first floating wind farm

- 5 floating turbines, 30 MW (more than 90 meters)

- World’s first commercial floating wind farm
- Situated 19 km off Peterhead, Scotland
- Five 6 MW Hywind floating turbines with a total capacity of 30 MW.
- Capacity factor is over 50%.
- Commissioned in October 2017.
Hywind Scotland: world’s first floating wind farm

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LCOE from utility-scale renewable power generation technologies, 2010 -2020

Source: IRENA, 2021.
Wind turbine price indices and price trends, 1997-2021

Global weighted average total installed costs, capacity factors, and LCOE for onshore wind, 2010-2020

Source: IRENA, 2021.
Global weighted average total installed costs, capacity factors, and LCOE for offshore wind, 2010-2020

Source: IRENA, 2021.
Average distance from shore and water depth for offshore wind, 2000-2020

Source: IRENA, 2021.
Wind power global capacity and annual additions, 2010-2020

Source: REN21, 2021

Wind power capacity and additions, top 10 countries, 2020

Source: REN21, 2021
Offshore wind energy global capacity, 2010-2020

Source: REN21, 2020
Wind power in the electricity mix, 2020

Share of total generation (%)

Source: REN21, 2021
Global Investment in Renewable by Technology, 2010, 2019 and 2020

<table>
<thead>
<tr>
<th>Technology</th>
<th>New Annual Investment (Billion USD)</th>
<th>Change relative to 2010</th>
<th>Change relative to 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar power</td>
<td>90.9</td>
<td>+64%</td>
<td>+12%</td>
</tr>
<tr>
<td>Wind power</td>
<td>89.0</td>
<td>+60%</td>
<td>-6%</td>
</tr>
<tr>
<td>Biomass and waste</td>
<td>10.3</td>
<td>-39%</td>
<td>-3%</td>
</tr>
<tr>
<td>Small-scale hydropower</td>
<td>1.7</td>
<td>-82%</td>
<td>-48%</td>
</tr>
<tr>
<td>Biofuels</td>
<td>1.7</td>
<td>-91%</td>
<td>-65%</td>
</tr>
<tr>
<td>Geothermal power</td>
<td>1.0</td>
<td>-73%</td>
<td>-30%</td>
</tr>
<tr>
<td>Ocean power</td>
<td>0.03</td>
<td>-100%</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: Figure includes utility-scale renewable energy and small-scale solar projects and excludes large hydropower projects of more than 50 MW.
Source: BloombergNEF. See endnote 29 for this chapter.
Renewable capacity reached 2799GW in 2020. Hydro accounted for the largest share (43%), with a capacity of 1211 GW. Solar and wind dominated capacity expansion.
Wind research at the Energy Centre
Spatial Effects of Wind Generation and Its Implication for Wind Farm Investment Decisions in New Zealand

Le Wen, Basil Sharp, Erwann Sbai

Abstract:
Spill-over effects on electricity nodal prices associated with increased wind generation have not been examined in the literature. To examine these effects, we use spatial econometric models to estimate the direct and indirect effects of wind generation on nodal wholesale electricity prices. Spatial econometric models allow us to provide quantitative estimates of spill-over magnitudes and statistical tests for significance. Results show negative and significant effects are associated with increases in wind penetration, and the effect is stronger during peak hours and weaker during off-peak hours. Simulation results demonstrate net savings of NZ$8 million per MW of additional wind capacity installed at the CNI2 wind site. The findings provide valuable information on the evaluation of wind farm development in terms of site location, wholesale prices, and financial feasibility. Our approach also contributes to forecasting location specific wholesale electricity prices, and provides a better understanding of the implications of locating wind sites.

Download Executive Summary  Purchase ($25)

Keywords: Merit-order effect, Spatial econometrics, Wind penetration, Nodal price, Wind investment

DOI: 10.5547/01956574.41.2.lwen
Wind energy expansion

Hourly Electricity Demand

Merit-order effect of wind power in different demand

Supply curve with high wind

Supply curve with low wind

$/MWh

Night
Shoulder
Peak

Delta Price at peak demand

Delta Price at night demand

P_{peak} (low wind)

P_{peak} (high wind)

Hours of day

Capacity in MW

0 5 10 15 20 25

0 1000 2000 3000 4000 5000 6000 7000

Hourly Load 2012 (MW)

peak

shoulder

night
Average wholesale price effects of an increase of 10% in wind.
What happens to wholesale price if there is a 10% increase in wind generation at BPE (Bunnythorpe)?
Where is the best place to build a wind farm?

Estimated net annual savings (million $) per MW installed
LRMC ($82/MWh)

- $0.61 mil
- $0.59 mil
$2.79 mil
- $0.32 mil
$0.77 mil
$1.79 mil
- $0.44 mil
- $0.19 mil
- $0.66 mil

Discussion

• Results show that private investment in additional wind capacity leads to positive gains in economic value.

• However, it’s not clear if private investment is financially profitable. Investing in capacity at a given node can reduce the return to a generator’s assets in the network.

• Reaching the goal of 20% electricity from wind generation depends on growth in demand. Maybe, this can come about from growth in electrification of transport.
Can hydro and wind be a good combination to stabilize the electricity price? A seasonal spatial econometric analysis in New Zealand

By Le Wen, Kiti Suomalainen, Basil Sharp, Ming Yi, and Selena Sheng

Exploring the complementarity of hydro and wind
Impact of wind–hydro dynamics on electricity price: A seasonal spatial econometric analysis

Le Wen a, Kiti Suomalainen a, Basil Sharp a, Ming Yi b,∗, Mingyue Selena Sheng a

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Merit-order effects

ABSTRACT

Hydro and wind are both commonly deployed renewable sources of electricity. Wind is intermittent and unpredictable to a large degree. Hydro depends on seasonal rainfall patterns, although storage may offer scope to spread the risk associated with dry seasons. We investigate the impact of intermittent wind generation, coupled with a given hydro capacity, on wholesale electricity prices, accounting for both spatial and seasonal effects. Results from a spatial Durbin model provide evidence of significant negative spill-over effects of wind generation on wholesale nodal prices. After robustness analysis with alternative spatial weight matrices, we provide estimates of the seasonal impact of wind generation on nodal prices using a transmission weight matrix. We evaluate seasonal nodal price effects during dry periods and wet periods in New Zealand’s hydro-dominated electricity market. Results show that the price reduction associated with a 10% increase in wind penetration varies across seasons, ranging from $0.48 per MWh in winter in 2012 to $3.05 per MWh in spring. The largest price reduction effect of 3.05 is found for the wet season in spring 2012, but the variance change is 3.6 which is less than 5.24 for the dry season in summer 2012. This evidence reveals that increased wind generation reduces nodal prices, as expected, but also increases the variance in nodal prices, particularly during a dry season. Thus, while a wind–hydro system is shown as a favourable low-carbon combination during wet seasons, without backup generation the system remains susceptible to price volatility. We further suggest policy recommendations to ensure the reduction of price volatility and the continuity of electricity supply during dry periods.
Wholesale price is affected by wet/dry season

Graphs showing wholesale price trends for the years 2011 and 2012, categorized by season:
- Spring: 2011 dry and 2012 wet
- Summer: 2011 wet and 2012 dry
- Autumn: 2011 wet and 2012 dry
- Winter: 2011 wet and 2012 dry

The graphs plot prices in dollars per megawatt-hour ($/MWh) against various locations (BPE, HAY, HLY, HWB, OTA, ROX, TIW, TKU, TWZ, WKM) for each season.
Wholesale Prices, Wind and Thermal Generation at HLY (Huntly)

- Price ($/MWh)
- Wind (MW)
- Thermal (MW)

22 Mar 2012, Thu
Variability of price

Seasonal price effects of a 10% increase in wind

<table>
<thead>
<tr>
<th>Year</th>
<th>Season</th>
<th>Price Change</th>
<th>Price Variance Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>spring(dry)</td>
<td>-1.51</td>
<td>9.84</td>
</tr>
<tr>
<td></td>
<td>summer(wet)</td>
<td>-0.09 (N.S)</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>autumn(wet)</td>
<td>-1.82</td>
<td>7.09</td>
</tr>
<tr>
<td></td>
<td>winter(wet)</td>
<td>-2.01</td>
<td>7.04</td>
</tr>
<tr>
<td>2012</td>
<td>spring(wet)</td>
<td>-3.05</td>
<td>3.60</td>
</tr>
<tr>
<td></td>
<td>summer(dry)</td>
<td>-1.49</td>
<td>5.24</td>
</tr>
<tr>
<td></td>
<td>autumn(dry)</td>
<td>-0.56</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>winter(dry)</td>
<td>-0.48</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Note: N.S indicates that coefficient is not significant
Lake Onslow

Formed in 1890 by the damming of the Teviot River and Dismal Swamp.
Pumped hydro storage?

• NZ Battery project
  ➢ Phase 1 Business case (2021) – investigation & evaluation ($30 m)
  A feasibility study on Lake Onslow and alternative dry-year solutions will be delivered in May 2022.
  ➢ Phase 2 (2022) – engineering design & field work ($70 m)
  ➢ Phase 3 (2022-2026) – construction
• Further development of wind can contribute to renewables target
• BUT evidence suggests an increase in price volatility
• Lake Onslow offers an option to meet anticipated growth in demand and moderate price volatility.
  • Is it economic? – we need the business case.
The OECD’s annual Economic Survey of New Zealand says
• “An example where caution would be required is the proposed NZ Battery Project.”
• “There is risk of abatement costs far higher than the NZ ETS price, and a risk of lower demand for emissions permits from electricity generators that lowers the permit price, resulting in lower-cost abatement elsewhere not occurring.”
Research on wind development feasibility studies at the Energy Centre

One of the alternative solutions -

• Offshore wind-to-hydrogen solution

• On-going research:

Are we lagging behind? Explore the potential of the offshore wind to green hydrogen system in New Zealand

With Cedric Chong and Stephen Poletti

Coupling offshore wind with hydrogen production will be one of main pillars towards a fully decarbonized energy system by avoiding wind curtailment, mitigating electricity grid congestion, and producing green hydrogen used for energy storage, transportation fuel, steel and iron production, or replacing natural gas for residential customers.

This project is to provide a pioneer study of assessing the feasibility of offshore wind and hydrogen production, including economic viability, challenges, and barriers. This study contributes to showing an alternative solution to achieve the New Zealand government’s net-zero carbon target.
On-going research:

Optimal Allocation of New Zealand Wind Generation

With Matthew Brunt and Stephen Poletti

This study uses an agent-based electricity pricing model to evaluate existing and potential wind farms by taking into account wind capacity, wind distribution, wind output variability, and electricity price, and to allocate optimal wind sites.
Climate change impact on the cost of decarbonisation in a hydro-based power system

Highlights:

• Climate change amplifies seasonal availability of hydro in New Zealand
• Climate change has indirect effects on optimal long-term energy system investments
• Cost of decarbonisation decreases slightly due to climate change in New Zealand
• Trade-off between solar and wind to support hydro under climate change

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Thank you for your attention!

“We cannot direct the wind, but we can adjust the sails.” – Dolly Parton

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