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Comparing and ranking the global cost of green industrial electricity

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Abstract: Australian governments at the commonwealth and state level have committed to achieving net zero greenhouse gas emissions by 2050. The policy is legislated at the commonwealth level and in some states. The commonwealth legislation includes an interim target of 43% reduction on 2005 levels by 2030 of which 22% had been achieved by 2022 (DCCEEW, 2022). Global net zero targets by national governments represent 91% of global GDP, 83% of global GHG emissions and 80% of the global population (Hans et al., 2022). 65% of these targets were legislated at May 2022. These statistics represent substantial growth on previous years indicating a growing consensus across the international community.

With the growing global commitment to greenhouse gas emissions reduction, export-based industries need to consider how the process of decarbonisation will impact their global competitiveness. The goal of the paper is to determine how likely it is that Australia will emerge as having a competitive industrial sector based on competitive renewable electricity supply. Early modelling of the impact of addressing climate change in Australia through emission reduction activities tended to find that Australia's emission-intensive industrial sectors would decline due to their high reliance on direct use of fossil fuels, fossil fuel-based electricity or fossil fuel export markets. In more recent modelling, results have suggested that global efforts to reduce emissions could result in a larger more globally competitive Australian industrial sector, with the exception of coal mining.

The significant change in the outlook is a result of a combination of five drivers:

- Renewable electricity has emerged to be a low cost source of green electricity
- Australia has large and diverse renewable resources
- The global energy transition is expected to drive growth in demand for Australia's mineral and metal production
- A global green hydrogen market is emerging
- Electricity is the least-cost greenhouse gas abatement pathway for the industry sector.

In the context of these developments, this paper seeks to provide a further investigation into whether Australia's renewable sources do provide it with a competitive advantage in industrial electricity supply. By drawing on a number of data sources and applying a linear program to 13 broad regions, made up of 194 sub-regions, we have been able to rank those regions in order of least to highest cost renewable industrial electricity supply. Based on the minimum cost in each region, the top three are India, Western Europe and China. Australia is ranked fourth but this rank could slip one place if Africa is able to exploit lower solar PV generation costs by 2050. Based on the average of all costs in a region, Australia's ranking improves to third, displacing Western Europe.

There are several important limitations on the analysis. It assumes that historical regional differences in regional costs remain static. However, costs of operating and deploying renewable generation technologies will change over time with scale and maturity of those industries and changes in the broader development status of those regional economies (i.e., wages tend to be higher as countries become more developed). Also, while we modelled 194 sub-regions, there remains a risk that important locations in each region have been missed. For example, the quality of onshore wind power is impacted by topology such as elevation, which was not considered. Some regions may also have been included that are not plausible. No process was undertaken to determine if the site was suitable due to competing land uses, access or conservation values.

Keywords: *Global competitiveness, electricity cost, green industry*

1. INTRODUCTION

Australian governments at the commonwealth and state level have committed to achieving net zero greenhouse gas emissions by 2050. The policy is legislated at the commonwealth level and in some states. The commonwealth legislation includes an interim target of 43% reduction on 2005 levels by 2030 of which 22% had been achieved by 2022 (DCCEEW, 2022). Global net zero targets by national governments represent 91% of global GDP, 83% of global GHG emissions and 80% of the global population (Hans et al., 2022). 65% of these targets were legislated at May 2022. These statistics represent substantial growth on previous years indicating a growing consensus across the international community.

With the growing global commitment to greenhouse gas emissions reduction, export-based industries need to consider how the process of decarbonisation will impact their global competitiveness. The goal of the paper is to determine how likely it is that Australia will emerge as having a competitive industrial sector based on competitive renewable electricity supply.

Early modelling of the impact of addressing climate change in Australia through emission reduction activities tended to find that Australia's emission-intensive industrial sectors would decline due to their high reliance on direct use of fossil fuels, fossil fuel-based electricity or fossil fuel export markets. The first major report was called *Australia's Low Pollution Future* (Treasury, 2008) where the modelling found that the two most impacted sectors were coal mining and aluminium. By 2050, across four scenarios, it was projected that aluminium production would be 45% to 62% below the reference case with coal mining 26% to 42% lower.

In 2011 a second report called *Strong Growth Low Pollution* followed (Treasury, 2011). By 2050 this updated modelling found a 62% to 74% reduction in aluminium production and 17% to 32% reduction in coal mining. The report also found that the iron and steel sector would experience a 21% to 31% reduction in output and other metals a 9% to 14% reduction.

In more recent modelling, results have suggested that global efforts to reduce emissions could result in a larger more globally competitive Australian industrial sector, with the exception of coal mining. In *Australia's long-term emissions reduction plan*, DCCEW (2021) presented updated results of a global scenario where developed countries commit to net zero emission by 2050 and limited the global temperature increase to below 2ºC. The projected reduction in coal mining is 51% by 2050 relative to the reference case. This worsened outlook for the Australian coal sector reflects that coal's potential future role in both domestic and global electricity generation has diminished owing to renewables emerging as a lower cost generation technology than the combination of coal with carbon dioxide capture and storage (CCS). Between 2010 and 2020, while the cost of coal with CCS remained largely the same, the levelized cost of electricity from wind and solar PV fell by 56% and 85% respectively (IRENA, 2021).

In contrast to coal mining, the outlook for heavy industry has not only reversed but is expected to be a major source of growth, increasing by 110% relative to the reference case. This significant change in the outlook is a result of a combination of drivers.

Australia has large and diverse renewable resources

The reduction in the cost of renewable electricity generation has meant that Australia may be able to supply more cost competitive low emission energy for industrial purposes given Australia has vast renewable resources relative to our energy requirements. In addition to vast renewable resources, Australia has a good mix of both wind and solar PV. Good quality solar resources exist in most mid to northern regions of Australia. Good quality wind resources exist in the southern part of the continent as well as other elevated parts of the country (DoI, 2014).

The global energy transition will drive growth in demand for Australia's mineral and metal production

The transition to clean energy technologies requires increased global production of critical energy technology minerals. Expansion of transmission grids is expected to require a doubling of aluminium and copper inputs to that sector. Construction of clean energy technologies such as electric vehicles, wind, solar PV and batteries is projected to support growth in demand of 42% in lithium, 25% in graphite, 21% in cobalt and 19% in nickel in addition to their current uses. Australia has a significant global share of these resources, particularly aluminium and lithium. Australia produces 31% of world bauxite production (the key precursor mineral for alumina) and around half of global lithium production. As demand for these resources grows, so long as Australia maintains its market share, growth in exports from the mining and metals manufacturing sectors can be expected (IEA, 2021a; Lord et al., 2019).

A global green hydrogen market is emerging

The emergence of hydrogen as a new global export market can potentially offset some reductions in fossil fuel mining exports. For countries that have limited domestic energy resource, and subsequently high fossil fuel imports, there is a growing need to find a low emission energy source for import that is consistent with their domestic 2050 net zero emission target. Hydrogen can potentially meet this need. While it is possible to produce hydrogen from natural gas with CCS, projected cost reductions in hydrogen electrolysers could mean hydrogen based on renewable electricity (green hydrogen) becomes cost competitive (ClimateWorks Centre 2023; Graham et al., 2022).

Electricity is the least-cost greenhouse gas abatement pathway for the industry sector

Owing to the large decline in the cost of renewable electricity generation, electricity will be the preferred fuel to decarbonise the industrial sectors of every country. For Australia, the *Pathways to industrial decarbonisation* report (Climateworks Centre and Climate-KIC Australia, 2023) has shown that a least-cost decarbonisation of the industrial sector would result in electricity's share of energy input increasing from around 20% in 2020 to 50% by 2050. This transformation is mirrored globally with the *World Energy Outlook* Net Zero by 2050 scenario projecting the electricity share of industry energy increasing from 17% in 2020 to 47% by 2050 (IEA, 2021b).

This paper seeks to provide a further investigation into whether Australia's renewable sources do provide it with a competitive advantage in industrial electricity supply. While there is little doubt that Australia's renewable resources are large and high quality, this description also applies to other regions of the world. The analysis gathers data on the relative quality of renewable resources around the world and uses a modelling approach to calculate the resulting industrial green electricity supply costs, providing a basis to compare and rank different regions.

2. METHOD AND DATA ASSUMPTIONS

2.1. Model design

To calculate the cost of green industrial electricity, the ideal approach would be to use a detailed electricity system modelling tool designed to represent the key details in each region such as the spatial layout of existing generators and transmission. However, maintaining and running detailed electricity system models of multiple world regions requires a large amount of resources. Instead, we exploit a number of features of industrial electricity supply to justify the use of a more abstracted electricity costing model design that is applied universally to each region, rather than using bespoke regional models.

A key feature of industrial electricity supply is that electricity is sourced through long term supply contracts. Industrial infrastructure is high cost and long-lived. As a result, the financing arrangements often include locking in electricity costs over an extended period of 10 to 20 years. Given the scale of industrial electricity needs, this can often mean that the whole output of the generation infrastructure is dedicated to that industrial customer. Transmission infrastructure may also be wholly dedicated to serving the industrial facility. Given this preference to contract dedicated resources, it is therefore not necessary to model the whole electricity system in each country, only the key generators that will be contracted.

For zero emission industrial electricity supply the key options are hydro, nuclear, solar PV and wind (onshore and offshore). There are other renewable technologies such as tidal power, however, these are not likely to be competitive with these existing options (Graham et al. 2022). Industry with access to existing hydro and nuclear are likely already very competitive because these technologies have very long asset lives. As a result, their capital costs are often already sunk. Substantially expanding global hydro power further is difficult due to limited topological features in non-environmentally sensitive areas. Nuclear power is expanding in some countries such as China, but it faces more difficult political barriers in developed countries.

Given the limitations on hydro and nuclear, the scope has been limited to modelling the cost of accessing solar PV and wind electricity generation. As such, the problem is one of securing sufficient solar PV and wind together with supporting storage and peaking generation technologies to meet industrial electricity supply. This new demand for industrial renewable electricity is already evident in the Australian aluminium sector, which has begun to test the market for gigawatt-scale renewable electricity supply (Rio Tinto 2022; Regan 2022).

The proposed model improves on existing work by taking advantage of the increased availability of hourly renewable production profiles at high spatial detail across the world. Such data is able to exploit satellite and other weather data sources to create hourly generation profiles. The past analysis by global modellers discussed in the introduction is primarily sourced from global general equilibrium model. Such models are not able to incorporate hourly generation profiles. They would instead include a broader statistic such as the average availability across the year (also known as the capacity factor). They might also group solar PV and wind technologies into a single renewable technology. As such, past modelling approaches may not have been reliable in assessing the industrial competitiveness of regions based on solar PV and wind electricity generation cost competitiveness.

2.2. Model description

The model is a linear program that minimises the cost of electricity supply from three generation technologies (gentech) – solar PV, onshore wind and offshore wind – two storage technologies (stortech) – batteries and pumped hydro – and peaking plant. The peaking plant is assumed to be natural gas. This means that the electricity is not strictly emission free. A hydrogen peaking plant would be an emission free alternative that could be explored in future models but would add extra complexity as the hydrogen becomes an additional source of electricity demand. The natural gas used is restricted to a maximum of 5% of total electricity supply in the model and its emissions could also be offset as a means of achieving a net zero emission outcome. The variables to be determined by the model and fixed data inputs or parameters are shown in Table 1.

Table 1. Model variables and parameters

Name	Description	Type
TotalCost	Total cost of electricity supply	Variable
$StorCap_{stortech}$	Storage technology capacity in MW	Variable
$GenCap_{gentech}$	Renewable generation technology capacity in MW	Variable
$PeakGen_{hour}$	Peaking generation	Variable
PeakCap	Peaking capacity	Variable
$SoC_{stortech,hour}$	State of charge of storage in MWh	Variable
$Char_{stortech,hour}$	Storage charge in MW	Variable
$Dischar_{stortech,hour}$	Storage discharge in MW	Variable
$storcost_{stortech}$	Amortised storage capital cost in $/kWh	Parameter
$duration_{stortech}$	Duration of storage in hours	Parameter
$gencost_{gentech}$	Amortised renewable generation capital cost	Parameter
peakcost	Amortised peaking plant capital cost	Parameter
$gomcost_{gentech}$	Renewable generator operating and maintenance cost	Parameter
$somcost_{stortech}$	Storage operating and maintenance cost	Parameter
peakomcost	Peaking plant operating and maintenance cost	Parameter
gasprice	Price of natural gas	Parameter
$renprofile_{gentech,hour}$	Renewable generation profile in MW/MW	Parameter
rteffstortech	Round trip storage efficiency	Parameter
$demand_{hour}$	Hourly industrial electricity demand	Parameter

The objective function and model constraints are as follows:

Objective function: minimises the total cost of electricity supply including capital, fuel and operating and maintenance costs

$$
\begin{aligned}
TotalCost = {} & \sum\nolimits_{stortech} StorCap_{stortech} \times duration_{stortech} \times storcost_{stortech} \\
& + \sum\nolimits_{gentech} GenCap_{gentech} \times gencost_{gentech} + PeakCap \times peakcost \\
& + \sum\nolimits_{stortech} Storcap_{stortech} \times somcost_{stortech} \\
& + \sum\nolimits_{gentech} GentechCap_{gentech} \times gomcost_{gentech} \\
& + \sum\nolimits_{hour} PeakGen_{hour} \times (peakomcost + gasprice)
\end{aligned}
$$

Demand-supply balance: supply must be equal to or greater than demand

$$
\begin{aligned}
& Peakgen_{hour} + \sum\nolimits_{gentech} renprofile_{gentech,hour} \times GenCap_{gentech} + \sum\nolimits_{stortech} Dischar_{stortech,hour} \\
& \quad \geq demand_{hour+} \sum\nolimits_{stortech} Char_{stortech,hour} \div rteff_{stortech}
\end{aligned}
$$

Maximum state of charge: state of charge cannot exceed storage capacity and duration

$$SOC_{stortech,hour} \leq StorCap_{stortech} \times duration_{stortech}$$

Maximum charge constraint 1: charge cannot exceed capacity of storage

$$Char_{stortech,hour} \leq StorCap_{stortech}$$

Maximum discharge constraint 1: discharge cannot exceed storage state of charge

$$Dischar_{stortech,hour} \leq SOC_{stortech,hour}$$

Maximum discharge constraint 2: discharge cannot exceed storage capacity

$$Dischar_{stortech,hour} \leq StorCap_{stortech,hour}$$

Evolution of state of charge: The state of charge next period is equal to the state of charge this period plus any charge minus any discharge

$$SOC_{stortech,hour+1} = SOC_{stortech,hour} + Char_{stortech,hour} - Dischar_{stortech,hour}$$

Starting state of charge: storage commences at half capacity

$$SOC_{stortech,hfirst} = 0.5 \times StorCap_{stortech} \times duration_{stortech}$$

Maximum energy contribution of natural gas: Gas cannot contribute more than 5% of total annual energy

$$\sum_{hour} PeakGen_{hour} \leq 0.05 \times \sum_{hour} demand_{hour}$$

Maximum generation from peaking gas plant: hourly generation cannot exceed capacity

$$PeakGen_{hour} \leq PeakCap$$

Key data assumptions

The source of all Australian generation and storage capital costs is Graham et al. (2022). Operating and maintenance costs and storage round trip efficiencies are from Aurecon (2022). However, to develop comparative costs between regions we have drawn on sources with global coverage of costs. Capital cost comparisons are drawn from IEA (2020). Differences in operating and maintenance costs are inferred from international wages data sourced from ILO (2020). Global gas prices are consistent with Graham et al. (2022), which draws on IEA (2021c). These sources allow us to account for the differences in costs experienced by different regions who are nevertheless installing an otherwise relatively generic group of technologies. Where data for a specific region was not available, data for a region of similar economic development was substituted. Based on these sources, Table 2 shows the differences in costs as an index where Australia is equal to 1.

Table 2. Index of differences in regional capital and operating and maintenance costs (Australia = 1)

Region	Solar PV capital cost	Onshore wind capital cost	Offshore wind capital cost	Storage capital cost	O&M cost	Natural gas cost
Africa	1.36	0.92	0.92	1.14	0.90	1.6
Australia	1.00	1.00	1.00	1.00	1.00	1.0
China	0.83	0.82	0.65	0.82	0.93	1.4
Eastern Europe	1.09	1.40	1.40	1.25	0.86	1.2
Western Europe	0.80	1.03	0.53	0.92	0.96	1.2
Former Soviet Union	0.80	1.03	1.03	0.91	0.88	1.2
India	0.71	0.61	0.61	0.66	0.86	1.5
Japan	2.27	1.59	1.18	1.93	0.95	1.5
Latin America	1.36	0.92	0.92	1.14	0.87	1.4
Middle East	1.36	0.92	0.92	1.14	0.97	0.6
North America	1.22	0.94	0.72	1.08	1.02	0.6
OECD Pacific	1.39	1.38	1.03	1.39	0.97	1.5
Rest of Asia	1.39	1.38	1.38	1.39	0.86	1.2

Renewable generation profiles that are a function of local climate and weather variation are the other major driver of differences of the economic performance of a solar PV and wind-based electricity generation. The hourly power output of wind and solar PV was sourced from Renewables.ninja, which is based on research by Pfenninger (2016) and Staffell and Pfenninger (2016). Renewables.ninja allows sourcing of this data for any location in the world, from 2010 to 2020. API access is available to download this data in bulk and a python API access was written to extract the data.

In total 194 points were selected, spread across the 13 regions created by overlaying a grid with locations spaced at 10 degrees both horizontally and vertically. Generation profile data was downloaded for a specific technology model. Solar PV used MERRA-2 dataset, no system loss, single axis tracking, with a tilt of 35 degrees and 180 degree azimuth. Wind data also used MERRA-2 dataset, a turbine height of 150m and a 'Siemens Gamesa SG 4.5 145' turbine. For offshore wind an ocean border was created for each region and extended 12 kilometres offshore. Along this offshore border, 195 hourly offshore wind generation profiles were extracted. These were matched by shortest distance to the existing onshore wind and solar PV sites.

Hourly industrial demand in each location is assumed to be 1000MW. Meeting this demand will require between 2 to five times that demand level in renewable generation capacity depending on the least-cost mix of solar and wind technology chosen by the model and the quality of those resources at each regional location.

3. RESULTS

The model was run for 8 weather years at each of the 194 sub regions for each of 2030 and 2050 technology cost data – a total of 3104 model results. To simplify the model outputs, we present the minimum and average cost calculated across all weather years and sub-regions for each of the 13 regions (Figure 1).

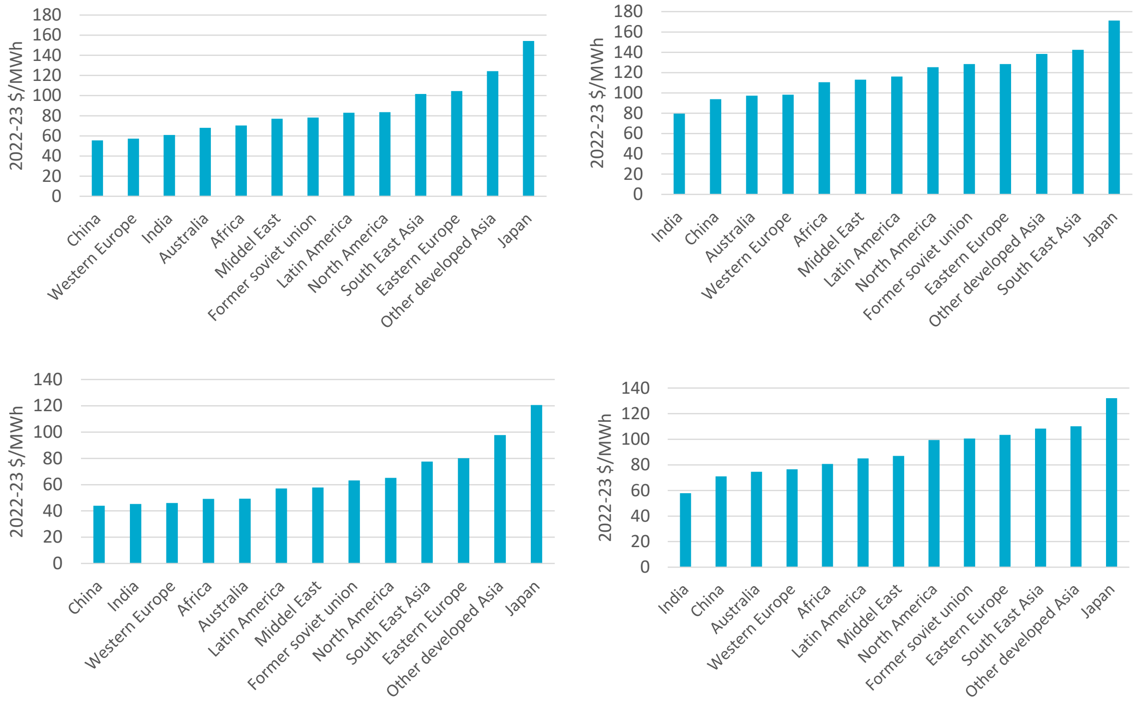

Figure 1. Ranked minimum (left) and average (right) cost of renewable industrial electricity in 2030 (top) and 2050 (bottom)

Of the 194 sub-regions, China, Western Europe and India rank as the three least-cost renewable industrial electricity suppliers in both 2030 and 2050, reflecting lower regional costs (Table 2) and the quality of renewable resources. The results indicate China has a particularly competitive sub-region, which ranks it first according to minimum costs, but India has lower costs than China on average. Australia's minimum costs rank fourth in 2030 and fifth behind Africa in 2050. This likely reflects greater use of good solar sites in Africa as stronger solar PV cost reductions (relative to wind) become a source of greater competitiveness for countries with good solar resources. On average costs, Australia is consistently ranked third. Japan and other Asia regions outside of India and China are consistently highest cost together with Eastern Europe reflecting their higher regional development costs. The Former Soviet Union is in the middle ranks. This reflects poorer quality renewable resources given its regional development costs are otherwise reasonably competitive. The Middle East and the Americas also rank in the middle but with the opposite driver – higher quality renewable resources but with some relatively high regional development costs for solar PV.

4. DISCUSSION AND CONCLUSION

This paper described global developments that are likely to result in electricity from renewable generation to become a key driver of industrial energy cost competitiveness. By drawing on a number of data sources and applying a linear program to 13 broad regions, made up of 194 sub-regions, we have been able to rank those regions in order of least to highest cost renewable industrial electricity supply. The top three regions are China, Western Europe and India. Australia is ranked fourth or fifth on a minimum cost basis but improves to third when measured on the basis of the average of its sub-regional costs, overtaking Western Europe.

There are several important limitations on the analysis. It assumes that historical regional differences in regional costs remain static. However, costs of operating and deploying renewable generation technologies will change over time with scale and maturity of those industries and changes in the broader development status of those regional economies (i.e., wages tend to be higher as countries become more developed). Also, while we modelled 194 sub-regions, there remains a risk that important locations in each region have been missed. For example, the quality of onshore wind power is impacted by topology such as elevation, which was not considered. Some sub-regions may also have been included that are not plausible. No process was undertaken to determine if the site was suitable due to competing land uses, access or conservation values.

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