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Towards a carbon neutral future

The Trilemma Scale

A decision support tool for the Energy Trilemma

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Abstract

The World Energy Council defines energy sustainability based on three dimensions: energy security, energy equity and environmental sustainability. The process of adequately addressing all three of these dimensions is commonly referred to as the Energy Trilemma. It is widely acknowledged that a range of low-emissions technologies will be required to meet the targets of the Paris COP21 agreement and that no single technology or class of technologies can efficiently and effectively supply all our energy needs. One of the issues policy makers must consider as they aim to achieve energy sustainability is the selection of power generation technologies to include in networks. Several indices are available to assist decision-makers to address the Energy Trilemma, but all have limitations for comparison of individual technologies.

Policy makers currently face three main challenges when comparing options for a sustainable energy portfolio.

- Diversity of characteristics of the technologies in terms of cost, reliability and emissions
- Consistency and transparency of data used in analysis of technology options
- Decision-makers come from a range of professional, political and ideological perspectives frequently bringing strong views about the relative importance of one of the three dimensions over the other two

An objective measure of performance is needed to support decisions around the Energy Trilemma.

A new decision support tool, the Trilemma Scale, was developed to inform the community and policy makers. This systematic, transparent and quantitative method incorporating measures of cost, reliability and emissions enables comparison of the contribution of each power generation technology to the Energy Trilemma. The comparative analytical data of each technology is transformed into a single metric – the Trilemma Score. The lower the score 'the better the solution' to the Energy Trilemma.

Conventional gas and coal fired generators fitted with carbon capture have the five lowest, most favourable scores when the Trilemma Scale is applied to contemporary data. Fixed renewables are sixth on this list. When the Trilemma Scale is applied to projected data to 2030, firm renewables move up to fourth place.

The findings highlight a mismatch between Trilemma Scores and current policies. Funding support, investment and rhetoric to address the future energy mix is heavily directed to technologies with higher, less favourable scores. For example, increasing the numbers of gas-fired plants with fast-acting open cycle turbines is being considered to address down-time of intermittent renewables and High Efficiency Low Emission coal-fired plants are being contemplated. Conversely little emphasis is given to options with lower, more favourable scores that address emissions from the existing high reliability and low cost fuel options. Although firm renewables are not yet commercial, they are on the policy horizon, but carbon capture and storage, which is steadily demonstrating viability, is not discussed as a serious contender for low emissions, low cost, high reliability power generation. These findings should stimulate debate and consideration of investment and commercialisation incentives.

Introduction

Energy trilemma

The World Energy Council (WEC) definition of energy sustainability is based on three dimensions [1].

- Energy security: effective management of primary energy supply from domestic and external sources, reliability of energy infrastructure, and ability of energy providers to meet current and future demand.
- Energy equity: accessibility and affordability of energy supply across the population.
- Environmental sustainability: achievement of supply- and demand-side energy efficiencies and development of energy supply from renewable and other low-carbon sources.

The process of adequately addressing these three dimensions is commonly referred to as the energy trilemma. A trilemma has been described as a choice between three unfavourable options or a trade-off between three goals in which two are pursued at the expense of the third [2]. The World Energy Council makes it clear that each dimension of the energy trilemma is based on desirable outcomes and all three must be achieved for energy sustainability.

"Balancing the three core dimensions of the energy trilemma is the basis for prosperity and competitiveness of individual countries. If the energy sector is to deliver on climate goals and support the achievement of development goals, it needs to do so in balance with the other two dimensions, to ensure sustainability of energy systems."[3]

Most power generation networks were designed prior to development of the current range of technologies, when choices were limited to fossil fuels and hydro. Improvements in reliability and efficiency have been made over time, but environmental considerations are relatively recent. Concerns about carbon dioxide and other pollutants have driven exploration of renewable energy sources and, even more recently, other low-emissions technologies.

It is widely acknowledged that a range of low-emissions technologies will be required to meet the targets of the Paris COP21 agreement and that no single technology or class of technologies can efficiently and effectively supply all our energy needs [4, 5]. The need for countries to accelerate development and wide-scale application of a diverse portfolio of clean, efficient, sustainable, low-emissions technologies has been highlighted [4, 6-10]. In addition, the cost to achieve emission targets will be lower from a portfolio of low emissions technologies.

One of the issues policy makers must consider as they aim to achieve energy sustainability is the selection of technologies to include in their power generation networks.

Comparison of technologies

Policy makers currently face three main challenges when comparing options for a sustainable energy portfolio.

The first is the diversity in characteristics within the range of technologies available. Conventional power generation from fossil fuels is low cost and has high reliability but produces significant CO_2 emissions. Renewables such as wind; solar PV and solar thermal have zero emissions but are currently more costly and less reliable than unabated fossil fuels. Over time, the introduction of batteries and storage systems is expected to make renewables more reliable and their costs will come down, but this is also true for research and development in all technologies. Hydroelectricity has no emissions, but when pumped hydro is introduced to increase reliability through stored energy, emissions are increased if power for pumping comes from conventional generators. Low emissions technologies such as coal, gas or biomass with carbon capture and storage (CCS) can significantly reduce carbon dioxide and other emissions while maintaining reliability, but at additional cost. While nuclear energy does not have carbon emissions, there are issues of radioactive waste to be considered. It is difficult to weigh up the advantages and disadvantages of such disparate technologies across the three dimensions of the trilemma.

The second is that the information available for decision-making is not always accurate, up-to-date or comprehensive. Current government subsidies only available to certain technologies are sometimes included in calculations, resulting in potentially significant underestimates of actual capital and operating costs for those technologies that benefit from the subsidies. Future cost estimates can also vary widely when they are based on different financing rates and the rates and other assumptions underlying calculations are not always made explicit. Capital costs of building new power generation assets do not usually include the costs of additional infrastructure required to integrate new facilities into the existing grid. Comparisons between technologies on a range of parameters are often presented as if they all operate 100% of the time without acknowledging that renewables are intermittent. Many reports comparing technologies do not include the most recent data available for all the options under consideration. These shortcomings lead decision-makers to incorrectly believe that they are comparing equivalent results.

The third is that decision-makers come from a range of professional, political and ideological perspectives, frequently bringing strong views about the relative importance of one of the dimensions of the trilemma over the other two. In addition, the current scientific literature in this area has *"…ignored the fact that the preferences among energy security, energy equity and environmental sustainability may change across decision makers, because of their competing relationships*."[11]

One of the benefits of expressing the three dimensions as a trilemma is that it makes the relationships and tensions between them explicit.[12] Traditionally, decisions regarding energy security and costs of power generation were independent of environmental policies. Addressing all three requires cooperation and collaboration between sectors. *"Until we get the environment, energy and commerce ministers in one room, we won't get good climate decisions*."[3]

If the environmental, reliability and cost parameters of individual technologies could be compared directly, good climate decisions could be made more effectively, and ministers' time used more efficiently.

Existing indices

Several indices are available to assist decision-makers to address the energy trilemma, but all have limitations for comparison of individual technologies. The World Energy Council Trilemma Index [1], Energy Justice Metric [6] and the Modified Markowitz Mean-Variance Portfolio Optimization Theory [13] were developed to inform strategies for national energy systems and the latter two are based only on financial indicators. The Australian Power Generation Technology Report compares individual technologies quantitatively based on cost, but comparison on a range of other indicators is qualitative [5]. To our knowledge, there is no index for comparison of individual technologies.

A systematic, transparent, quantitative method to characterise individual technologies across all three dimensions of the energy trilemma is warranted.

Trilemma Scale

The Trilemma Scale enables comparison of the contribution of each power generation technology to the energy trilemma based on cost, reliability and emissions. It transforms the comparative analytical data of each technology into a single metric – the Trilemma Score.

The WEC energy trilemma has been represented as a Venn diagram where the overlapping triangle in the centre represents ideal sustainable energy development and the remaining areas show the interdependence and trade-offs between each of the three dimensions of the energy trilemma [14]. The same principles can be applied to the Trilemma Scale where the triangle at the centre is the Trilemma Score (Figure 1).

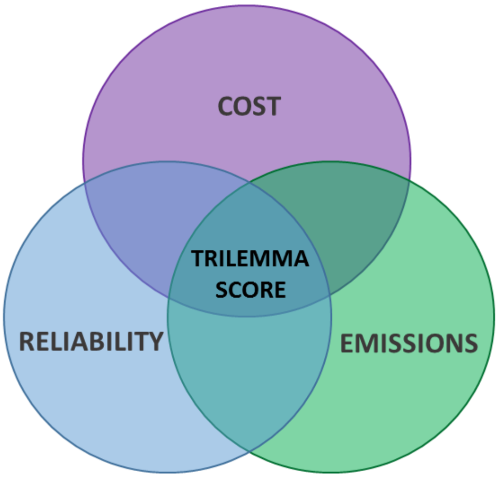


Figure 1. The Trilemma Score

Trilemma Scores for a range of technologies could be one of several inputs to decisions selecting a preferred energy mix. Although other parameters may affect final project selection, the scale offers an initial framework to enrich the debate on pathways to a cost-effective, reliable, low emission future.

Analysis of a range of low emissions technologies including renewables (intermittent and firm), existing and new-build conventional power plants (coal and gas), CCS (new-build and retrofit, with and without partial capture), is presented to compare their fundamental performance capabilities with respect to the three components of the energy trilemma in the Australian context.

Context

The Trilemma Scale has been developed and applied from the perspective of power generation in Australia. Application of the Trilemma Scale in other contexts simply requires selection of relevant technologies and input of appropriate data.

When making comparisons, it is important to remember that countries, and even local regions, differ in critical aspects such as fuel costs, labour costs, available resources, power generation mix, etc that may limit direct extrapolation of international data in these areas. For example, in the United States gas is cheaper and coal more expensive than they are in Australia. Nuclear energy is used in many countries but is not allowed by law in Australia. Within Australia, CCS has greater feasibility in Victoria than New South Wales due to the location of suitable geological reservoirs close to power plants.

Methods

A cost, reliability and emissions score was calculated for each technology. These scores were combined to form the Trilemma Score.

The lowest value is the preferred outcome. This applies to the scores for the three individual components and to the total Trilemma Score for each technology.

The scale can be produced for different time periods using projected cost improvements over time and so provide an indication of preferred future pathways. Two scenarios were considered in this pilot: calculations were undertaken on recent data and projected data to 2030.

Technologies

The Trilemma Scale has been piloted with a range of power generation technologies where data regarding their performance in the Australian context are available.

- **Natural gas** generators include 'open cycle' (NGOC) plants, where waste heat produced in the process of electricity generation is released, and the more efficient 'closed cycle' (NGCC) plants, where waste heat is used to generate additional electricity via a steam turbine. Comparisons are made between the current models of operation (CO_2 emissions released unabated) and potential models which include carbon capture (CO_2 emissions captured).
- **Coal** generators include black and brown coal in conventional power plants and the proposed High Efficiency Low Emission (HELE) plants. Comparisons are made between the current models of operation (CO_2 emissions released unabated) and potential models which include carbon capture (CO_2 emissions captured).
- **Renewables** include wind and solar. Australian data to allow inclusion of hydroelectricity are not available [5]. Comparisons are made between the current models of operation as 'intermittent renewables' (electricity is only generated when the wind blows and the sun shines) and the potential model of 'firm renewables' (batteries, back-up facilities and transmission infrastructure enable the same reliability as existing fossil fuel power plants).
- **Carbon capture** can be retrofitted to existing gas and coal fired generators or incorporated into new builds. Retrofitting reduces the output from a power plant and this was accounted for in the calculations. Partial capture can be deployed to allow the amount of CO_2 emissions captured to be varied from 0 to 90%. The electricity costs and emissions of partial capture are inversely related, one increases as the other decreases, hence lower CO_2 reductions can be achieved at significantly lower costs than the 90% base case. Costs for storage of captured CO_2 were included. The retrofit CCS options (with partial capture) are based on previously published brown coal studies linked to Bass Strait storage. Black coal CCS retrofit is expected to provide similar outcomes however retrofit projects are highly individual and scope specific.

Indicators

- **Cost** is measured using 'Levelised cost of electricity' (LCOE) [5]. LCOE represents the cost of producing electricity over the entire life of a technology by combining capital costs, operating costs and, where applicable, storage costs. This allows direct comparison of technologies with very different cost profiles. For example, renewables, which are capital-intensive but have low operating costs, can be compared with fossil fuels, which have a balance of capital and operating costs, using this single indicator. The LCOEs for current and proposed technologies are publically available (see data sources noted below). The intrinsic generation cost is used for existing forms of generation and variable renewables. However additional costs for batteries (various forms) and additional transmission infrastructure is necessary for firm renewables. CCS costs are generally for 90% CO_2 removal with modifications for partial capture and cost improvements through to 2030. More detail on the benefits, costings and opportunities of partial capture are available in the references [15]. Costs for renewables are frequently presented in the media at much lower rates than those cited in the data sources used in this pilot. To investigate the effect of lower prices on the Trilemma Score, a sensitivity analysis was conducted. Wind prices were reduced by 50%, solar by 35% and firm renewables by 10%.

- **Reliability** relates to capacity within the power system to provide sufficient electricity to meet all consumer demand [16]. Reliability measures consider generation, battery storage in renewable systems, transmission and distribution infrastructure. The 'reliability standard' for the Australian National Electricity Market (NEM) is the primary mechanism to signal the market to deliver enough capacity to meet consumer demand. This is currently set at 0.002% unserved energy (USE) per region per financial year, which means that out of 100,000MWh of demand, no more than 2MWh of outage would be allowed [16]. Reliability is generally achieved by backups, often referred to as redundancy, such that if one item fails another is available. The probability of backups not achieving the reliability standard is calculated by multiplying the probability of any one unit not being available. This is based on the online time for any given technology. The probability of not being available is mathematically (1- online time probability). For a conventional power plant, the online probability is typically 0.85, therefore 0.15 probability of not being available. Based on these figures, triple redundancy (the probability of not being available raised to the power of 3) was felt to most closely approximate the NEM standard of 0.002%; quadruple redundancy seemed too tight a constraint. The Trilemma Score calculations were based on triple redundancy, however sensitivity analyses using the power of 2 and a single online measure were calculated to provide comparisons.
- **Emissions** data for conventional power plants are publicly available (see data sources noted below). Renewable energy generators have zero source emissions.

Data sources

Cost data were sourced from the Australian Power Generation Technology Report [5], CSIRO Low Emissions Technology Roadmap [17], UNOTech Response to the Preliminary Report of the Independent Review into the Future Security of the National Electricity Market [15] and Bloomberg New Energy Finance Australia Insight [18].

Data from the Australian Power Generation Technology Report [5] were used for Reliability and Emissions.

Normalisation

Individual technologies generate a characteristic value for each parameter (cost, reliability and emissions). The diversity of technologies produces a broad range of values for each indicator. For example, LCOE ranged from $30/MWh to $250/MWh. These data are 'normalised' for translation to a single manageable scale. The absolute values are divided by the respective parameter range to yield a value between 0 and 1. The normalised values are multiplied by their respective weighting and summed to get the Trilemma Score for each technology.

Weighting

The Trilemma Scores presented in the Results section below are based on calculations giving equal weight to each dimension. However, as noted earlier, some decision-makers may choose to give preference to one or two dimensions over the other/s [11]. To illustrate the differences resulting from a range of preferences, sensitivity analyses were undertaken with unequal weighting. A factor of two was applied to each parameter individually (cost, reliability and emissions) and to the three possible combinations of pairs (cost and reliability, cost and emissions, reliability and emissions).

Results

Components

As expected, costs vary across the whole range of technology options; intermittent renewables perform poorly and the fossil fuel technologies perform strongly on reliability; and the reverse is true for emissions where renewables significantly outperform fossil fuels.

Trilemma Score

The Trilemma Scale is presented visually with the technologies in ascending order based on their Trilemma Score. Technologies to the left of the graph, with the lowest scores, are more favourable based on a combination of their cost, reliability and emissions. Technologies to the right of the graph, with higher scores, are less favourable.

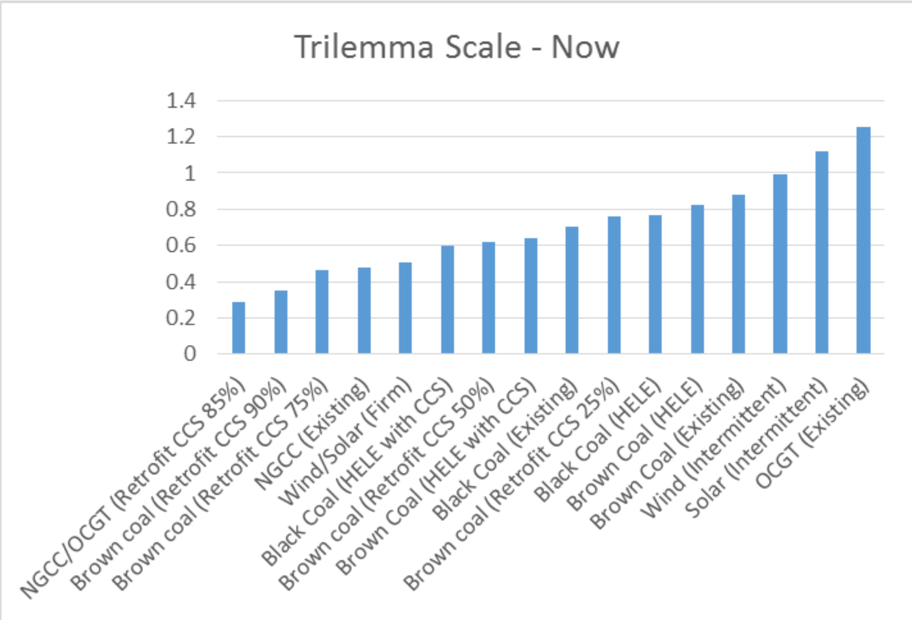


Figure 2 Trilemma Scale - Now

Figure 2 shows the outcomes based on recent data. Findings include:

- The lowest, most favourable, scores are coal or gas fired generators with CCS, three are existing models with carbon capture retrofitted, one is a new build natural gas closed cycle with CCS.
- Retrofitting CCS improves the scores of existing coal and gas fired power generators considerably.
- The addition of CCS improves the score of new builds considerably although Natural Gas Combined Cycle is the only one in the most favourable group.
- New build coal options (HELEs) without carbon capture are not appreciably better than existing unabated options as they trade off minor emissions reduction with higher LCOE and reliability is unchanged. When CCE is added, HELEs only move into the middle range.
- Firm renewables is the fifth lowest score, a position greatly improved from intermittent renewables.
- Intermittent renewables have some of the highest, least favourable scores due to high cost and low reliability.

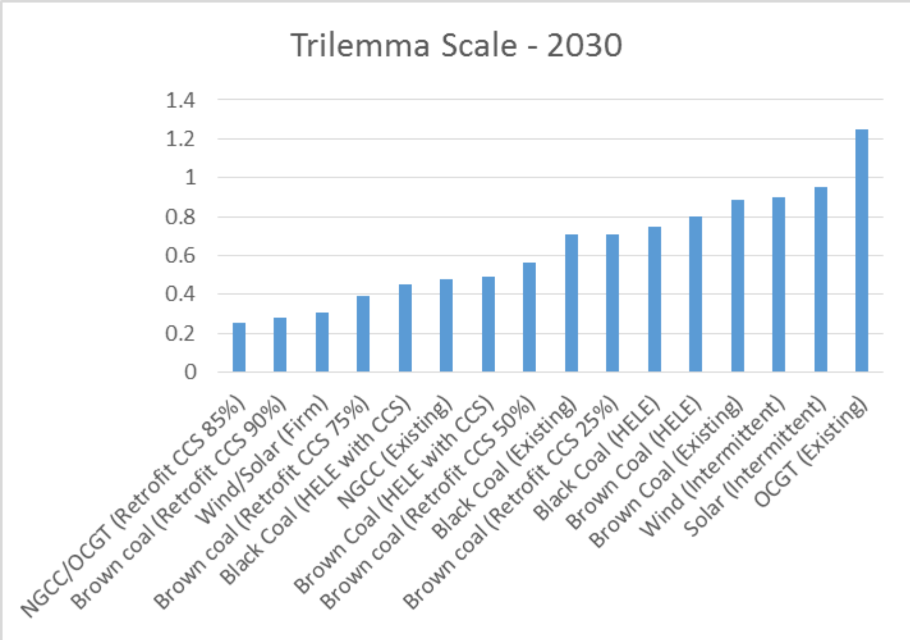


Figure 3 Trilemma Scale – 2030

Figure 3 shows the outcomes based on projected data for 2030. Findings include:

- Retrofitting carbon capture to existing coal and gas options still provides desirable outcomes.
- Due to anticipated cost reductions, firm renewables move up to third position, while intermittent renewables remain at the least favourable end of the scale.
- Unabated new build gas and coal options are unchanged.

Sensitivities

- **Reliability** (Appendix A): The Trilemma Score calculations were based on triple redundancy, however sensitivity analyses using the power of 2 and a single online time measure were calculated to provide comparisons. This favours technologies with lower availability, those with greater 'down time'. Firm renewables moved up from fifth to third position, but intermittent wind and solar remain at the least favourable end of the scale.
- **Weighting** (Appendix B): Similar to the reliability sensitivity, altering the weightings for a single parameter or combination of two parameters does not fundamentally alter the ranking or findings of the Trilemma Scale. They do demonstrate some bias to an individual's preference, however the impact is such that it is hard to justify moving from equal weighting. This finding demonstrates the merit of considering all factors together as a guide to the best energy trilemma outcome.
- **Low Cost Renewables** (Appendix C): As would be expected, lowering the costs improved the firm renewables score, moving it from fifth to third position. Intermittent wind moved one place to the left but wind and solar remain at the least favourable end of the range.

Limitations

This is the first application of the Trilemma Scale. While this pilot produces useful information to stimulate debate and research, it is likely that it can be refined for future use.

The findings are based on a selection of technologies with consistent data available for the Australian setting at the time [5]. In other settings, additional technologies such as nuclear power or hydroelectricity could be added.

While LCOE is a useful tool, it does not include all the components that might be considered. Other non-financial benefits may also have cost implications; such as whether the technologies being compared provide baseload power, power for peak periods, and/or have the ability to ramp supply up or down to meet demand.

Emissions have only been considered as CO_2 production from power generation. Under these conditions, renewables are considered to have zero emissions however, if a life cycle analysis was undertaken, emissions from the manufacturing process would also be included.

Other parameters such as radioactive waste could be added.

Discussion

There is no question that renewables are the energy sources of the future, but the future where we can rely on renewables for secure, affordable power is still some way off. If we are to provide affordable and reliable power, achieve the most effective and cost-effective reduction of CO_2 emissions in the foreseeable future, and meet our international commitments and targets, the discussion must become 'technology-neutral' and all available low emissions technologies must be considered.

The Trilemma Scale provides a vehicle to compare all power generation technologies with regard to cost, reliability and emissions reduction. Those on the left of the graphs have better outcomes across all three parameters, and those on the right have poorer outcomes. This information can be used in policy discussion and development. Sensitivity analysis suggests that, in its current form, with equal weighting to each trilemma parameter, the Trilemma Scale provides a robust tool for decision making. Including consistent, up-to-date and valid data for each technology is the most important requirement.

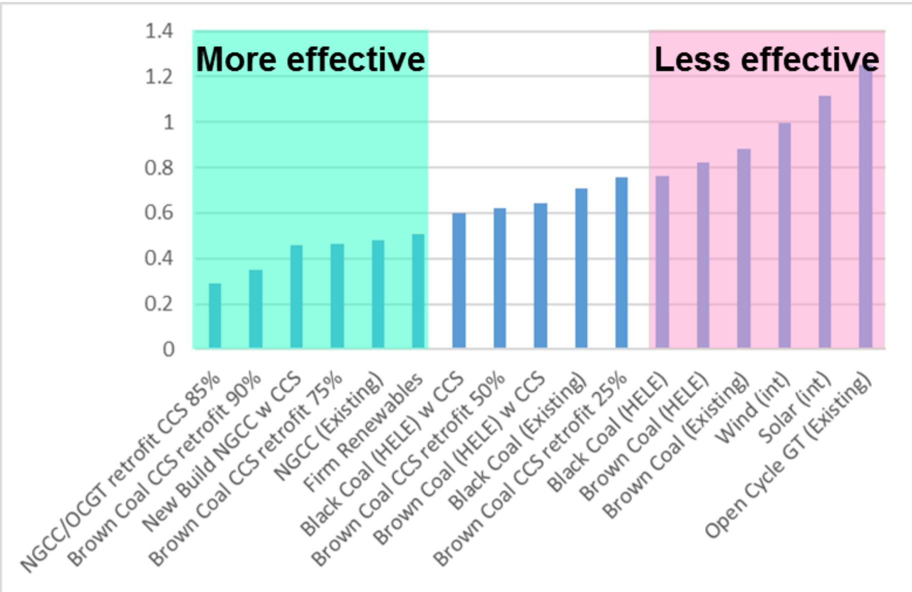


Figure 4. Mismatch between current policy and Trilemma Scores

The findings highlight a mismatch between Trilemma Scores and current policies. Funding support, investment and rhetoric to address the future energy mix is heavily directed to technologies with higher, less favourable scores (Figure 4 pink). For example, increasing the numbers of gas fired plants with fast-acting open cycle turbines is being considered to address down-time of intermittent renewables and High Efficiency Low Emission (HELE) coal fired plants are being contemplated. Conversely, little emphasis is given to options with lower, more favourable scores that address emissions from the existing high reliability and low cost fuel options (Figure 4 green). Although firm renewables are not yet commercial, they are on the policy horizon; but carbon capture and storage, which is steadily demonstrating viability, is not discussed as a serious contender for low emissions, low cost, high reliability power generation.

Reducing the emissions intensity of existing infrastructure through CCS retrofits could create more options for the NEM and provide better interim solutions to counterbalance intermittent renewables until firmer options become more cost effective.

Technologies on the right hand side of the graph still have benefits. Although OCGT is high cost and relatively high emissions, it is highly responsive, so supports reliability of the grid by meeting sudden demand.

Calculations for this pilot were based on data from the 2015 APGTR report. Since then, gas prices have increased considerably, which would push natural gas options further to the right of the graph. Coal and their CCS variants, on the other hand, are likely to either hold their Trilemma Scale position or improve.

All low emissions technologies have a higher cost than unabated (no treatment/removal of CO_2 emissions) power.

Technology and cost improvements are occurring in all low emissions technologies.

Increased CCS knowledge now makes retrofit to existing power plants viable, irrespective of age, efficiency and fuel type. In cases where plants have sufficient residual life and access to storage reservoirs, a strong case can be made for retrofit. The ability to retrofit capture to any existing power station has been developed here in Australia and validated on overseas demonstration projects. This offers a cost effective, reliable, low emissions power proposition. The difference in results between such retrofits and new-build with CCS is considerable. New disruptive capture designs currently being trialled are expected to further reduce costs of low emissions fossil fuel power while capturing up to 100% of CO_2 emissions. This may be available as early as 2020.

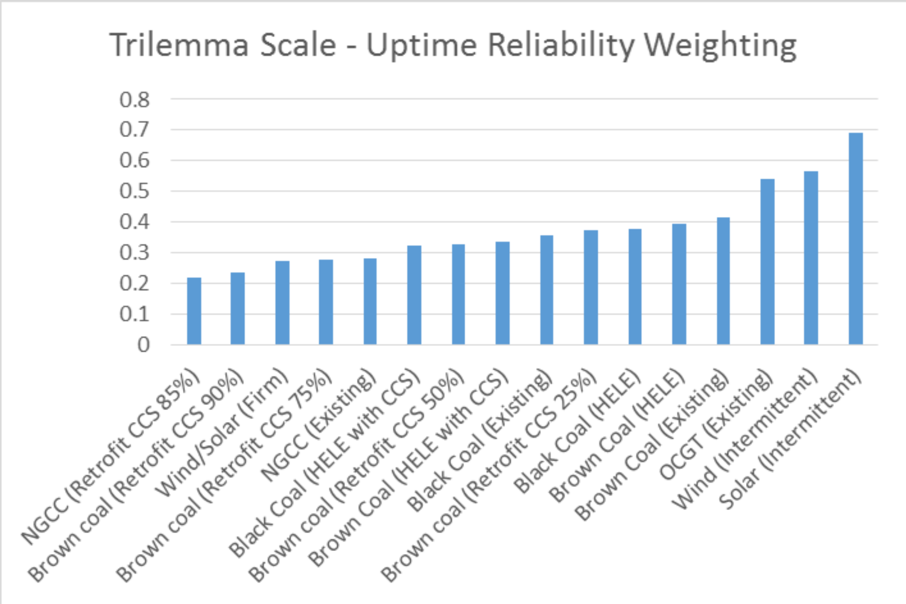
Summary and Conclusions

A new tool, the Trilemma Scale transforms the comparative data for each technology into a single metric, the lowest of which represents the best 'solution' to the energy trilemma. The resulting graphs identify a mismatch between current policies and the Trilemma Score. Funding support, investment and rhetoric to address the future energy mix is heavily directed to technologies that score poorly and little consideration is given to those scoring favourably.

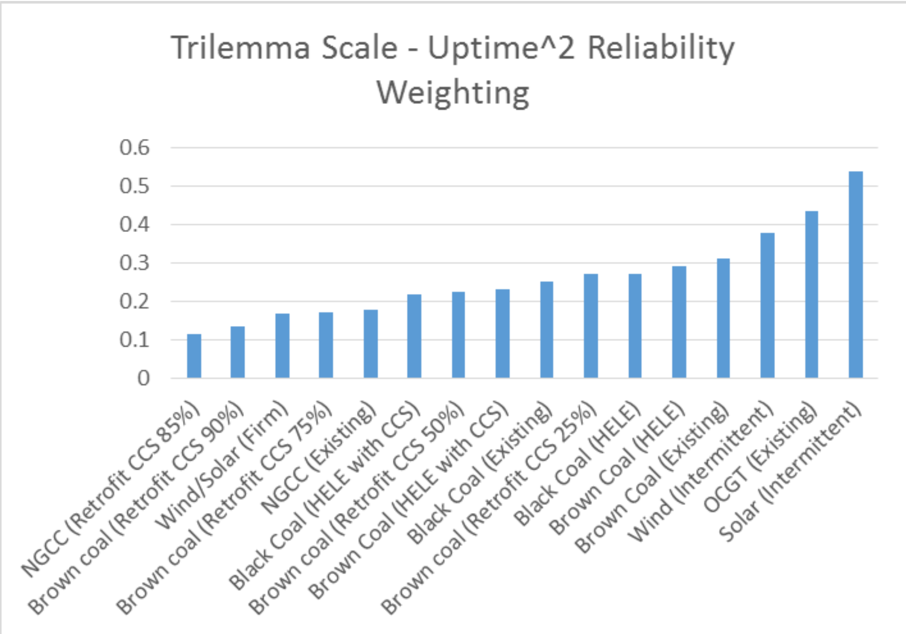
These findings should inform policy making and encourage debate and consideration of investment and commercialisation incentives.

Appendix A. Sensitivity analysis for Reliability

Reliability for single redundancy

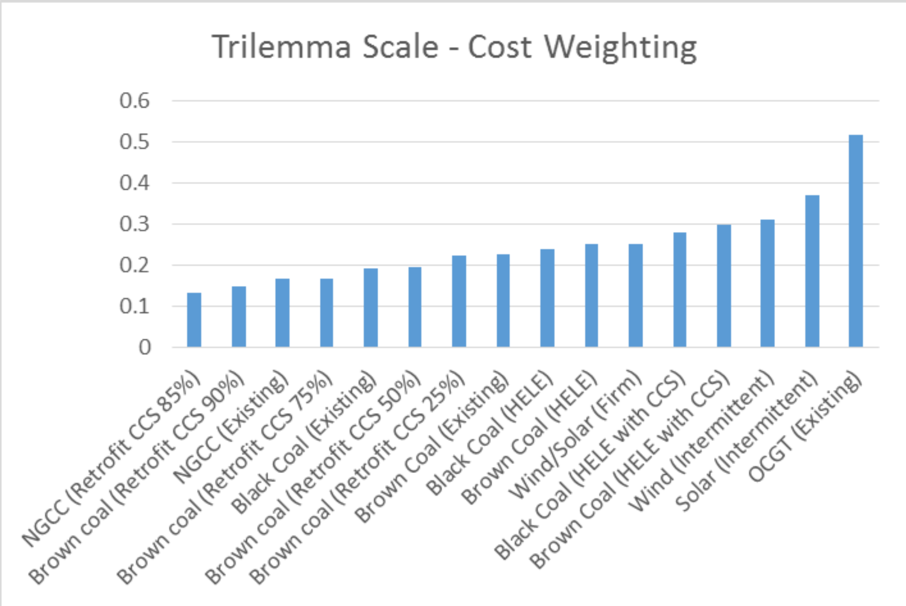


Reliability for double redundancy

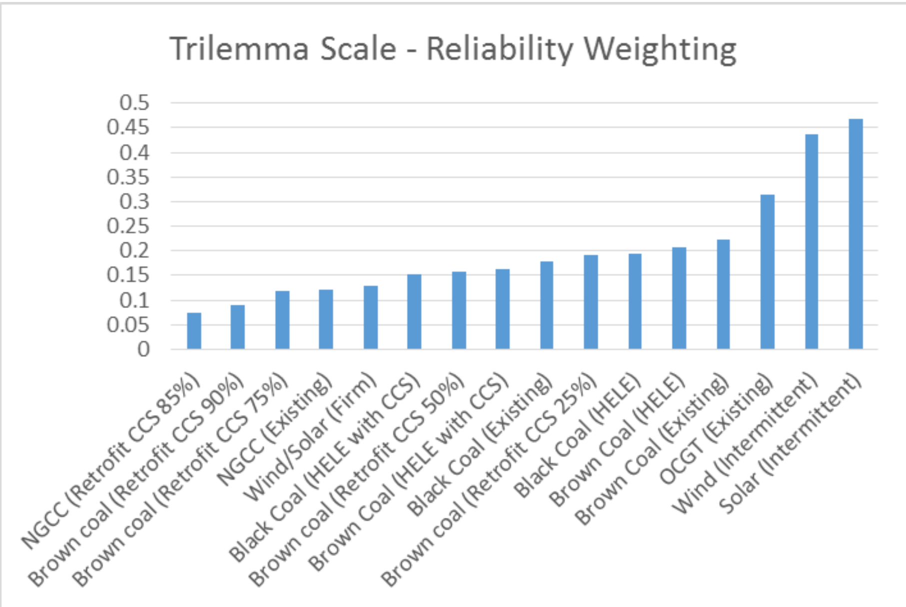


Appendix B. Sensitivity analysis for Weighting

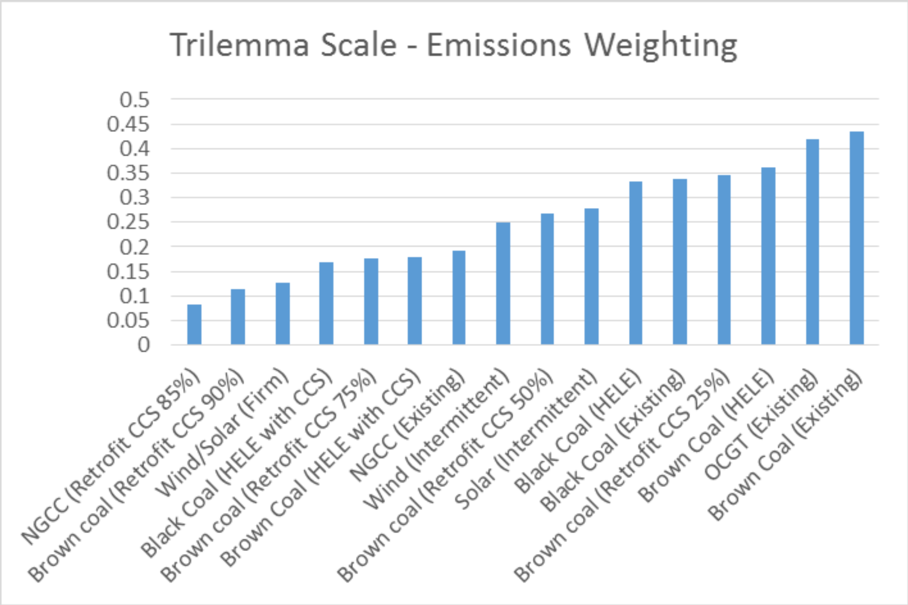
Cost weighted x 2



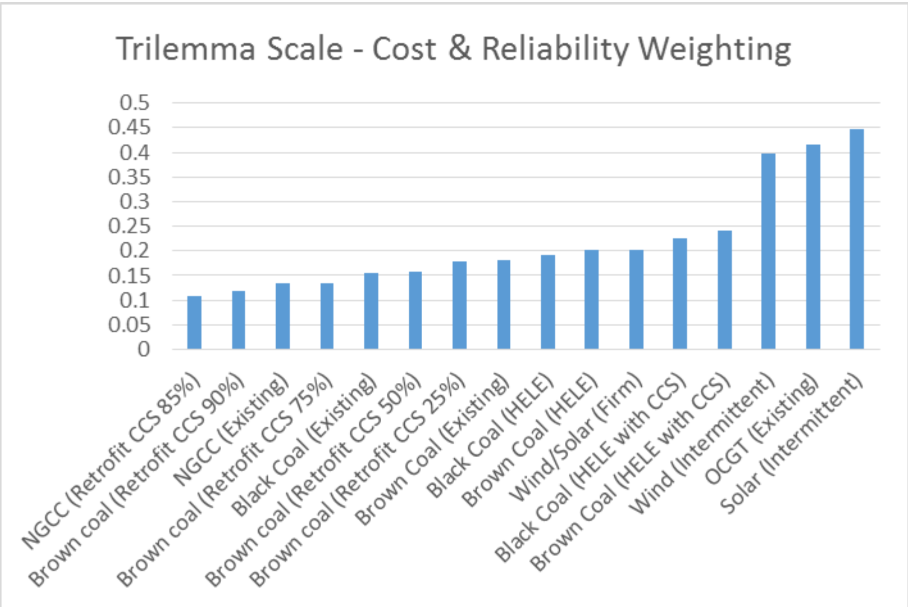
Reliability weighted x 2



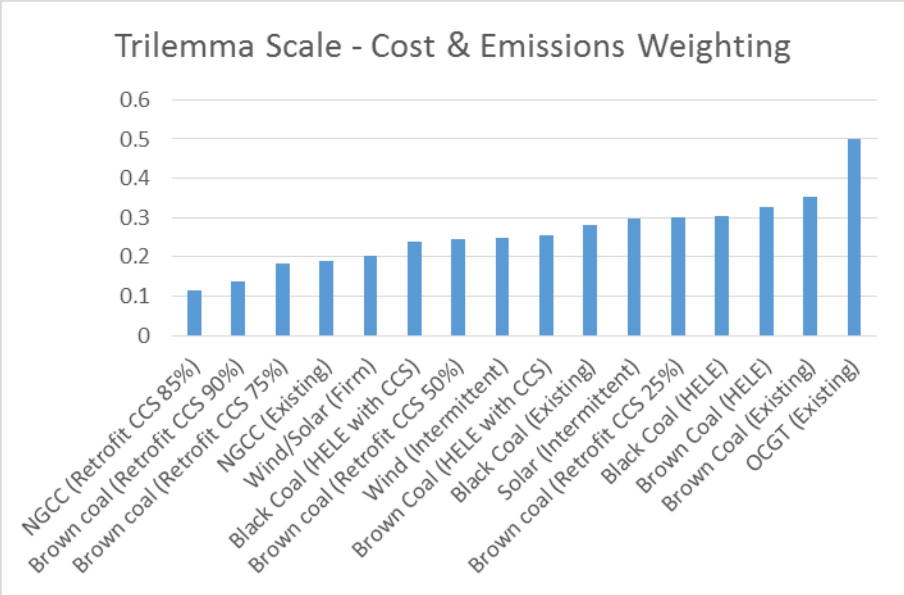
Emissions weighted x 2



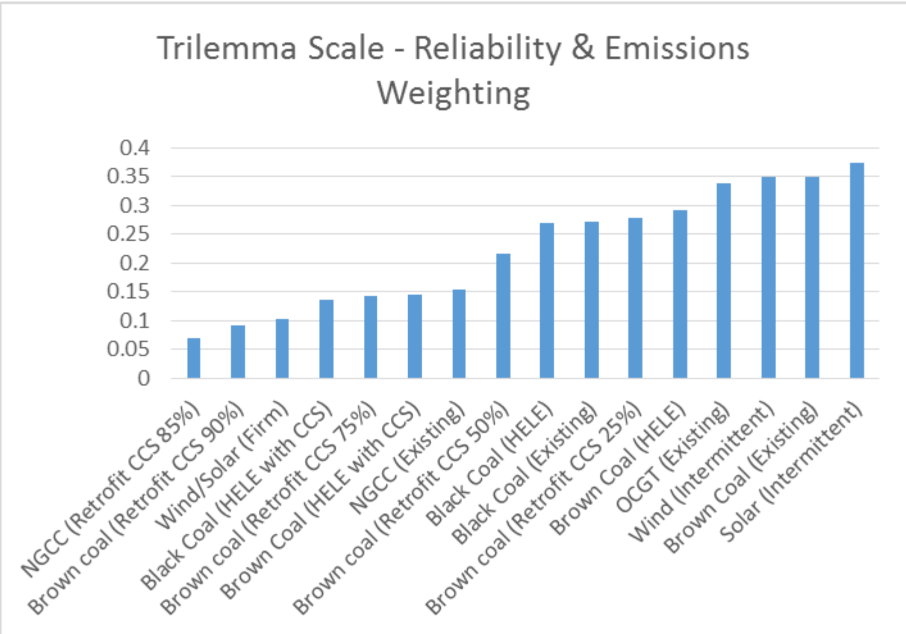
Cost and Reliability weighted x 2



Cost and Emissions weighted x 2

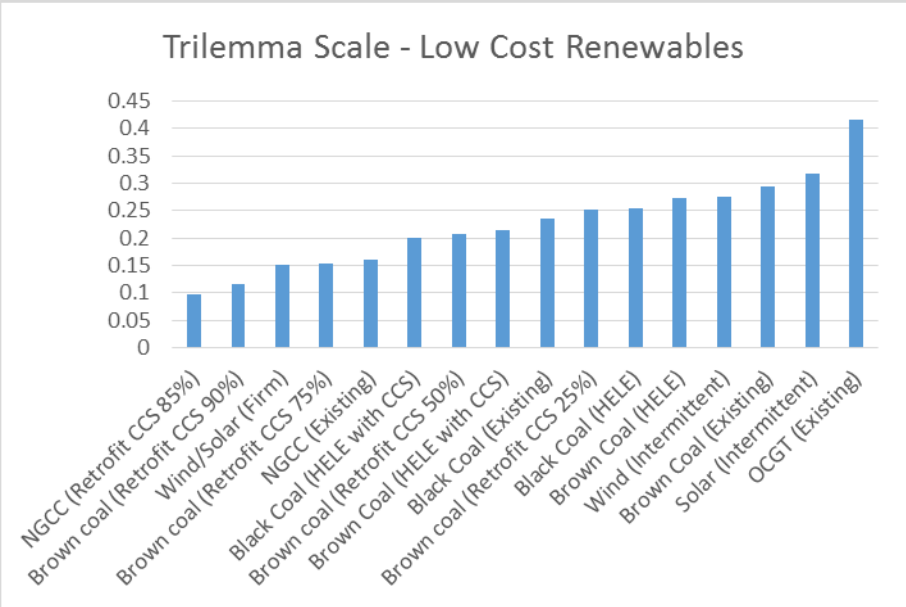


Reliability and Emissions weighted x 2



Appendix C. Sensitivity analysis for Low cost renewables

Low cost renewables



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