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Victoria's Energy Transition using n Bottom Line Analysis

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Abstract: To achieve net-zero emissions by 2050, Australia must decarbonise the energy sector and other sectors. The 'energy transition' is driven by policy-led construction of renewable infrastructure and regulation changes. However, no holistic analysis of the path forward currently exists. This research aims to develop a clear plan for Victoria's energy transition by evaluating three scenarios. A Business as Usual (BAU) scenario is compared against two alternative solutions. The alternates emulate two of Victoria's possible trajectories. Alternative 1 (ALT1) focuses on Victoria's reliance on imported interstate renewable energy, while Alternative 2 (ALT2) involves Victoria becoming self-sufficient through renewable generation. Each of the three scenarios is compared across four bottom lines: technical performance, social, economic, and environmental. Interviews among energy experts revealed that economic and social metrics were considered most important. Applying the n-bottom line (nBL) assessment framework delivers a result that finds ALT2 and ALT1 tied as the preferred solution. Hence, the construction of renewable infrastructure in Victoria and increased interstate transmission capacity should be built. Further research could include a deeper understanding of the embodied carbon in infrastructure built for the energy transition.

Keywords: Energy transition, Victoria, Mixed-method, Renewable energy, N bottom Line, Electricity, Carbon

Abbreviations:

- AEMO is the public-private entity that manages Australia's electricity system
- AGL is a large Australian electricity generation and retail company
- BAU, ALT1, ALT2 are ALT3 are the scenario labels in this research
- CO2e stands for CO2 equivalent and is a standard measure
- DB stands for Distribution Business
- GHG stands for Greenhouse Gas

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- LCA stands for Life Cycle Assessment
- nBL stands for n Bottom Line and expands on triple bottom line analysis.
- MW stands for Mega Watt, which is an instantaneous measure of electricity
- MWy stands for Mega Watt years which is a time-based measure of total electricity
- VPP stands for a virtual power plant (digitally tied smaller generators and batteries)
- $ are Australian dollars unless marked as US$, which are USD.

1. Introduction

The global energy transition occurring throughout the first half of the 21st century is driven by increased greenhouse gas emissions and local air pollution, altering the Earth's geophysical processes, and warming its surface. The Paris United Nations Climate Conference[34] created the framework for lowering greenhouse gas emission strategies. Despite this guidance, the energy transition encompasses cascading effects across energy system structures, policy regulation and integration, and social reaction, and Victoria must devise a path forward that balances these.

Australia has the highest greenhouse gas emissions per capita globally. Traditionally, Australia's electricity supply has depended heavily on abundant black and brown coal (lignite). Victoria has an estimated 430 billion tonnes of in-situ lignite in natural reserves. However, Victoria's coal-based infrastructure is aging and described as 'fragile'. For example, Yallourn Power Station, which supplies about 20% of Victoria's electricity, should close four years before the original 2032 schedule[10]. The retired coal station will become a 350 MW capacity battery facility, enabling the progression of renewables in the energy mix. The Victorian Government supports the aim to achieve net-zero by 2050[7].

Current obstacles to Australia's energy transition include policy, regulation and sociotechnical systems, which inhibit renewable technology from fulfilling its potential[9]. This research aims to develop and test three scenarios for Victoria's energy transition. The first plan will adopt a Business as Usual (BAU) approach to the Victorian energy industry, assuming all planned infrastructure upgrades and shutdowns will go ahead as scheduled. The first alternative (ALT1) models a scenario where all of Victoria's electricity is imported across state borders. The second alternative (ALT2) is a scenario where all of Victoria's energy is generated by renewable methods within the state. Each plan will have inherent differences in policy and regulation to facilitate the changes.

The three scenarios will then be assessed across four bottom-line indicators: technical performance, economic, social, and environmental. The n-bottom line (nBL) assessment framework will evaluate each solution across a range of quantitative metrics selected for each bottom line. A final score for each solution will be derived through normalisation and weighing the individual bottom-line metrics. The application of the nBL framework provides a pathway to find the most effective solution for Victoria to proceed with the energy transition.

2. Literature Review

The literature selected covers the energy transition globally and literature pertinent to Victoria's geopolitical context. The 'Energy Transition' is the decarbonisation of energy generation and the corresponding changes in energy system structure, policy and regulation required to facilitate this change, as well as the social change in how people use energy[9]. The energy transition can be fundamentally traced back to decarbonisation. However, it is more than a change in the generation method and includes an important role for electricity customers, and correspondingly Australia's energy transition faces challenges: a highly dispersed grid; widespread use of air-conditioning systems; a high concentration of solar photovoltaic (PV) systems;

rapid increases in electricity costs for both the consumer and distribution businesses (DB's)_ENREF_8. These challenges require energy policy and governance systems to align with climate change policy.

Dr Alan Finkel's An Independent Review into the Future Security of the National Electricity Market: A Blueprint for the Future, commonly referred to as the 'Finkel Review'[13], supplies a framework and pathway for reform in energy policy. The Finkel Review was commissioned in response to the 2016 South Australian blackouts. Encompassing a total of nineteen policy recommendations, Finkel identifies the role of consumers and solid governance as two key areas to aid the transition.

The importance of effective governance for the energy transition is also a central theme in the literature. Using South Australia as a case study[27] suggest that the polarity of inherent ideological values between Australia's two largest political parties has stunted investment and participation in renewable technologies. On a broader scale[6] details Australia's approach to energy policy as a reflection of the "starts, somersaults and reversals" of national climate change policy[36] agrees with this train of thought, stating that the uncertainty created by the changes in Australia's climate change policy has "paralysed" the energy sector and "stifled" investments in technologies. However, the government is not the sole party responsible for the transition's success. In analysing global energy transitions[26] shows that regulatory agencies and public and private firms share accountability for a functioning energy sector through the transition[26] argues that a two-phase approach to industry transformation exists. Phase 1 is centred around the uptake of recent technologies (e.g., renewables), with reinforcement in public policy to support these technologies[36] notes that whilst some public policies incentivise renewable investment, the fruition of these policies creates technical challenges on the grid. Reverse current and overvoltage resulting from high concentrations of PV systems connected to existing low voltage infrastructure cause difficulties in the control and operation of grids, specifically when these systems feed energy back into the circuit[19]. Voltage control problems are prevalent in Australia, where many homeowners have invested in PV systems (due to Government rebate schemes). Markard also notes that utility companies oppose or ignore the technologies in the first phase. The argument that utilities will ignore recent technology aligns with Weller's analysis of AGL, one of Australia's largest generation-retail ('gen-tailer') companies, and their role in the monopolistic nature of the electricity market. With the successful purchase of Macquarie generation assets in 2014, AGL's portfolio included 65% coal-based and over 80% fossil fuel-based generation. Until 2015, AGL actively used its position to "shape regulation to reflect and advance its interests"[36].

A change in business approach throughout the mid-2010s saw AGL announce closures of coal-based infrastructure and adopt a progressive approach towards climate change[36]. However, Weller concludes that the future of AGL and, in general, Australia's energy industry depends on "favourable government policy settings" (p. 449). Phase 2 of Markard's energy transition distinctly refers to large actors who initially opposed or ignored the recent technologies being profoundly affected by the change, such as gen-tailers and DB's. Markard stresses the need for policy to help system integration for intermittent renewables as a key driver for implementing phase 2. Such policy development is a central topic of discussion among industry leaders, who see the implementation of smart technologies as an opportunity to ensure demand meets supply while simultaneously ensuring the grid operates within safe boundaries[9]

Victoria holds a promising position to act on the benefit of smart technologies due to the rollout of smart meters within the state. Demand-side management is an important method of reducing grid challenges associated with renewable technologies[17], argue that implementing smart technologies can remove the threat of power outages through ongoing monitoring, diagnostics, and protection. The liberation of smart meter data away from DB's will drive innovation, and demand-side management combined with storage enables a broader range of business models to enter the market[2].

Harnessing smart meter information to make informed decisions on the grid network is part of a larger effort to place consumers at the centre of energy grid markets. One study on household interactions with smart energy systems showed that, in general, consumers are willing to cooperate with DB's to enhance energy management systems[29, 39], suggest that while consumers have a significant role, some are restricted. Restrictions for low-income households include borrowing constraints, and low income, preventing these households from installing renewable energy systems[39].

The Finkel Review[13] proposes that energy consumers in Australia are not rewarded for their contributions to reducing peak demand. Finkel indicates that the retail market should offer real value to consumers. As well as generating this direct value for consumers, consumer engagement strategies such as gamification and financial incentives should also be implemented to encourage people to change their consumption behaviour[32].

Studies suggest that Australian retail markets do not offer similar consumer benefits compared to overseas markets[37] state that Australian retail electricity markets are "categorised by profit margins" and argue these are higher for Australian retailers than their overseas counterparts and argue that confusing product offerings and lack of innovation contribute to low consumer engagement levels. Supplying feedback technologies (e.g., smart meters) contribute to the energy transition through greater provider-consumer cohesion, awareness, and willingness to change consumption behaviour will accelerate the transition[3] ENREF_32.[5] expand on this idea, arguing that smart technologies will only bear fruitful results if consumers invest the time and energy into "understanding, evaluating and reflecting" their consumption levels.

In summary, the global energy transition literature reveals challenges associated with the technical performance of renewable grid systems and the role of consumers and energy stakeholders (i.e., distributors, gen-tailers, market operators) in enabling and fulfilling the transition. The energy transition encompasses inherent variables among social, economic, environmental, and technical performance bottom lines. Above all this, the role of energy policy and Government action has a profound influence on the energy transition's success. As a result, Victoria's energy transition plans must be built with a holistic framework that critically assesses various indicators.

3. Methodology

The literature shows trends and challenges to the progression of renewables. This research is to advance the discussion by applying the lessons from the literature to develop three energy transition scenarios for Victoria[30] state that the holistic evaluation of newly proposed technologies is a "very important step" in optimising and implementing its real-life application. The research will culminate with quantitative and qualitative assessment forms to understand the dynamics unique to each hypothesis.

3.1 BAU and Alternative Proposals

Three scenarios for Victoria's energy future were derived.

A Business as Usual (BAU) scenario assumes all planned renewable projects will progress on schedule.

The first alternative solution (ALT1) would simulate Victoria's energy industry if new renewable energy were sourced entirely across state borders. The coal-fired generation will be phased out rapidly to achieve an energy mix of 100% renewables by 2030. Therefore, only BAU renewable generation projects would take place inside Victoria (except rooftop solar), while investment in transmission capacity would increase along with storage.

The second alternative solution (ALT2) will simulate Victoria's energy industry if all renewable energy is sourced within state borders. This scenario involves heavy investment in renewable generation, transmission, and storage to support the changes and stability needed, again with coal-based infrastructure phased out rapidly to achieve an energy mix of 100% renewables by 2030.

Appendix A summarises the proposed solutions and the required changes, while Appendix B summarises the proposed generation mixes. We subject each scenario to policy and industry effects to derive a measure.

The parameters for each scenario were found by assessing planned projects.

For the BAU, projects on the Planning Victoria website were included if approved or under construction. Coal taking up the rest of the energy mix in 2030.

Potential projects for ALT1 and ALT2 and the BAU projects were derived from proposal reports found online, which have been lodged for approval but not accepted.

Following the establishment of each solution and detailed analysis of required projects to achieve peak demands (shown in Appendix D), the first form of quantitative assessment, the nBL Analysis, can begin as detailed in Section 3.2.

3.2 nBL Analysis

Quantitative assessment will take place in n-bottom line (nBL) analysis. Application of the nBL framework enables comparative analysis by selecting objective metrics which characterise and reflect individual bottom lines (e.g., environmental, social, economic)[15]. Therefore, each proposal is analysed across identical metrics, supplying a pathway to comparatively assess the results. The nBL assessment process was applied to Victoria's three energy transition scenarios. This process was applied to four bottom lines: social, economic, environmental, and technical performance. The following section will display the nBL process applied to each bottom line. BAU, ALT1 and ALT2 proposals are compared by first quantifying the performance of each metric and then by calculating an overall value of each bottom line. The analysis will use forecasts for 2030, considering data estimated from now 2021 to 2030.

In order to undertake nBL analysis across the three scenarios, metrics representing each of the four bottom lines must first be selected. Section 3.3 will outline the methods adopted to select and quantify each metric. The chosen metrics are technical performance, social, economic cost and environmental, and each is described in Section 3.3.

3.3 Detail for nBL Analysis

3.3.1 Technical Performance

Our selection of metrics to describe the technical performance of the energy system was guided by the literature[12]. This research assessed losses associated with converting potential energy to electricity and transmission losses. Next, utility-scale storage capacity was measured based on the projects unique to each proposal (see Appendix D). Finally, transparency of data between relevant grid operators and stakeholders was measured. Methods adopted to calculate second-level metrics for each technical performance, along with any assumptions and justifications, are shown in Appendix E.

3.3.2 Social

The literature suggests employment outcomes are central to the social measure of transitions. Our method used ten years of annual average construction and permanent operational jobs for each new project (Appendix F).

We also estimated health effects over ten years and considered the plan to close Yallourn Power Station in 2028. This health measure included annual deaths, underweight births, and childhood asthma attributed to brown coal[21, 14]. People impacted by the emissions from these power plants were assumed to be distributed between the three coal plants and assessed yearly (Appendix F)

As a proxy measure for customer engagement between DB's and energy receivers used measures of public complaints about renewable projects (Appendix F).

3.3.3 Economic Cost

Capital costs are a major roadblock to the rapid uptake of renewables, with key decision-makers hesitant to invest too heavily too quickly[22].

Externality costs are another significant factor in this cost analysis. The value of the world's biosphere is US$33 trillion, and the external cost of GHG emissions has been estimated to cost society anywhere from \$5.5/tCO2e up to \$500/tCO2e[18]. Appendix D shows our calculations for:

Capital cost.

Operation and maintenance (O&M) cost.

External costs due to GHG emissions.

Appendix G provides further detail.

3.3.4 Environmental

The energy transition uses resources[35]. Managing how the materials for renewable energy infrastructure are sourced, processed, manufactured, constructed, and disposed of are vital components in accommodating a more viable future. Hence, projects for each scenario were evaluated

Appendix H shows the steps of our method and the assumptions made.

3.3.5 Application of nBL Assessment

Once the raw metric values of each bottom line have been compiled, the nBL assessment can be applied, with the process of normalising, standardising, and aggregating the data into a final score discussed below.

Raw values (RV) are normalised to remove units and allow for the comparison of different metrics. The normalisation process delivers an index between 0 and 1 by incorporating a theoretical best value (BV) and worst value (WV), as shown in Equation 1.

$$\text{Normalised Value (NV)} = \frac{RV - WV}{BV - WV} \qquad (1)$$

Preferences between individual metrics are collated through an interview process and standardised to develop a hierarchy. As part of a formal interview process discussed in Section 3.3, interviewees were asked to rank each metric in order of importance within each of the four bottom lines. The results across all interviews are then averaged to determine an overall hierarchy. Standardising each metric involves finding the inverse of each average result and standardising these inversed values. Hence, the sum of all metrics about a unique bottom line equals 1. The values were found from the standardised weighting value for each metric.

The next step involves an additive aggregation method using Equation 2.

$$\text{Aggregated Indicator (AI)} = \frac{1}{k} * \sum_{i}^{n} W * NV \qquad (2)$$

k = the number of datasets (i.e., the number of second-level metrics) of each metric

W = relative weight of importance of each metric, found in the standardisation process.

The three steps associated with the nBL assessment framework are repeated to obtain aggregated values for bottom lines for the three scenarios. Hence, applying the nBL process will return a single numerical value for each scenario.

3.4 Interviews

Following the metrics selection and data collation, interviews with key industry leaders began. Various leading energy industry representatives were contacted and interviewed to obtain insight into their thoughts and opinions on various characteristics of the energy transition. The first type of question asked required interviewees to rate the importance of different interventions and actions in facilitating the transition. These ranged from questions about the importance of governments engaging with energy consumers to the importance of infrastructure upgrades, including storage facilities and interconnector transmission lines. The second set of questions asked subjects to rank the relative importance of the metrics to evaluate the most effective proposed transition. The purpose of these questions is discussed in detail in Section 3.3. The last section of the survey was a series of worded response questions asking professionals about the catalysts, risks, policies, and other fundamental characteristics. Responses from these questions will provide discussion points exploring the practical application of the nBL assessment and challenges which will arise throughout the transition. The original survey used in the interviews can be found in Appendix K.

4. Results

4.1 Technical performance

Table 1 summarises the raw metric results for the technical performance bottom line, accompanied by the best and worst values required to normalise metric values, as described in Section 3.2. The corresponding normalised values are also provided in Table 1.

TABLE 1: tabulation of technical performance metric values accompanied with best, worst, and normalised values.

From Table 1, the best value for conversion loss assumes zero generation within the state of Victoria and hence, zero conversion losses. A generation mix of 100% coal was assumed for the worst value since coal conversion to electricity possesses the lowest efficiency rate of all generation methods at 28%. The best and worst values for transmission losses were compared to global data in the literature. Singapore has the highest efficiencies across their network at 2.03% of energy lost, while Togo has the lowest efficiency of 29% (71% lost)[38]. Defining the values of storage capacity in our modelling proved to be challenging. Since the total amount of storage for each solution was calculated in 2030, the best value was assumed to be the largest storage capacity for any region globally. China plans to install over 30GW of energy storage by 2030[31], more than any

	Data			Best		Worst		Normalised		
Metric	**BAU**	**ALT1**	**ALT2**	**Value**	**Evidence**	**Value**	**Evidence**	**BAU**	**ALT1**	**ALT2**
Conversion Loss (%)	68.09%	58.74%	58.53%	0.00%	No generation (100% imported)	72.00%	100% Coal [23] (Kazi, 2014; 24] (MacKay, 2008);	0.05	0.18	0.19
Transmission Loss (%)	9.86%	11.77%	11.12%	2.03%	Singapore [38] (World_Bank, 2018)	71.00%	Togo [38] (World_Bank, 2018)	0.89	0.86	0.87
Storage Capacity (MW)	380	1730	4784	30000	China 2030 target [31] (Reuters, 2021)	0	No storage	0.01	0.06	0.16
Data Transparency (-)	1.67	2.00	2	2	Theoretical max. from formula [4] (Brazier et al., 2020)	0	Theoretical min. from formula [4] (Brazier et al., 2020)	0.84	1.00	1.00

region in the world. Hence this value was adopted as the best realistic value possible. The worst value adopted is logically zero. The theoretical formula (see Appendix E) to determine data transparency values inherently have maximum and minimums. As a result, these theoretical maximum and minimum values were adopted.

After standardisation and aggregation, we applied the weightings in Table 2. These weightings are a single value summarising the overall technical performance for each bottom line. The full interview results and derived weightings are provided in Appendix I. The final aggregated values are shown in Table 3.

TABLE 2: summary of derived weightings for each technical performance metric from the results presented in appendix i.

Technical Performance	Transmission Loss	0.20092
	Conversion Losses	0.20785
	Battery Storage	0.31724
	Data Transparency	0.27398

TABLE 3: final aggregated values about the technical performance bottom line.

	BAU	ALT1	ALT2
Aggregation	0.11	0.13	0.13

4.2 Social

Metric results about employment, health and public satisfaction are shown in Table 4. Raw data values are shown, with their normalised indices also presented after incorporating the 'Best' and 'Worst' values for each second-level metric.

TABLE 4: tabulation of social metric values accompanied with best, worst, and normalised values.

The highest value for employment was determined by multiplying the jobs created from ALT1 by 20% to conservatively accommodate the potential for more required construction workers in the transition. The worst value for employment was zero jobs created in extreme circumstances, such as outsourced work or no renewable projects

	Data			Best		Worst		Normalised		
Metric	BAU	ALT1	ALT2	Value	Evidence	Value	Evidence	BAU	ALT1	ALT2
Employment	2380	3091	4610	5813	Higher workers required, calculated as 20% higher than ALT2	0	No jobs (e.g., all outsourced from overseas)	0.41	0.53	0.79
Health	37046	21611	20068	18524	Yallourn, Loy Yang A and Loy Yang B both closed by 2028	46310	Yallourn, Loy Yang A and Loy Yang B remain in operation in 2030	0.33	0.89	0.94
Public Satisfaction	219.6	219.6	319.5	0	No complaints	439	If 'other' complaints were all wind. Total increased by 20%	0.50	0.50	0.27

being developed. The best and worst values for health outcomes were determined by all power plants closing by 2028 or remaining in full operation in 2030. The best-case scenario for public satisfaction is if no complaints are made during the transition. Conversely, the worst-case scenario is determined by attributing all ‘other’ complaints to wind farms[1], then multiplying the overall total by 20% to accommodate the possibility of additional complaints.

The individual normalised results for each metric were then aggregated. Table 5 shows the relative weightings of each social performance metric, which are then aggregated to determine the social outcome for each of the three scenarios, as shown in Table 6.

TABLE 5: summary of derived weightings about each social metric derived from the results in appendix 1.

Social	Employment	0.45051
	Health	0.28669
	Consumer Engagement	0.26280

TABLE 6: final aggregated values about the social bottom line.

	BAU	ALT1	ALT2
Aggregation	0.16	0.23	0.25

The results show that the ALT2 transition proposal is best, closely followed by ALT1.

4.3 Economic

The individual second-level economic metric results are shown in Table 7. The raw data values are shown, with their normalised indices also presented after incorporating each metric's 'Best' and 'Worst' values. These best and worst values were determined by assuming:

- For the externality costs of GHG emissions metrics, the best-case scenario assumes net-zero emissions, a cost of 0, and the worst-case scenario assumes a 100% coal generation mix.
- For the capital costs, the best-case scenario assumes zero expenditure on infrastructure, and therefore a cost of 0. The worst-case scenario

assumes a further expenditure on carbon-reducing infrastructures, such as carbon capture and storage.

- For the operational costs, the best-case scenario assumes maintenance-free infrastructure. Therefore, a cost of 0, and the worst-case scenario, assume a "do nothing" approach. All energy is imported and paid for accordingly.

The calculation of second-level metric results is detailed in Appendix G.

TABLE 7: tabulation of economic metric values accompanied with best, worst, and normalised values

c	Data			Best		Worst		Normalised		
Metric	BAU	ALT1	ALT2	Value	Evidence	Value	Evidence	BAU	ALT1	ALT2
Externality Cost of GHG Emissions (US$m)	29072.75	19797.89	16950.48	0.00	Net zero	52822.00	100% coal generation	0.45	0.63	0.68
Capital Costs ($m)	9738.32	16951.54	29196.73	0.00	No new infrastructure	45196.73	Fully renewable infrastructure (ALT2) + further heavy investment in carbon reduction technologies	0.78	0.62	0.35
Operation ($m)	6759.07	11976.59	7076.84	0.00	maintenance-free	30000.00	Do nothing, import all electricity	0.77	0.60	0.76

TABLE 8: summary of derived weightings about each economic metric derived from the results presented in appendix 1.

Economics	Externality Cost of GHG Emissions	0.469
	Capital Costs	0.305
	Operation	0.226

TABLE 9: final aggregated values about the economic bottom line.

	BAU	ALT1	ALT2
Aggregation	0.208	0.207	0.200

Table 9 describes the final aggregated results of the economic metric, preceded by their relative weightings determined from the interview process in Table 8. These results show that the BAU is the preferred economic solution but merely more preferred than ALT1, with ALT2 being the least preferred economic solution. A sensitivity analysis of how the results change from changing important input values is available in Appendix L.

4.4 Environmental

The individual second-level economic metric results are shown in Table 10. The raw data values are shown, with their normalised indices also presented after incorporating each metric's 'Best' and 'Worst' values. Further details on calculating the results for each second level metric are detailed in Appendix H. GHG emissions metrics best-case scenario assumes coal generation to cease instantly. Therefore, a 510.34 kt CO2 eq value for new renewable infrastructure is applied. The worst-case scenario is based on coal generation continuing at current emission rates until 2030 with the combination of emissions from introduced renewable infrastructure, reflecting a value of 270221.98 kt CO2 eq. For our measure "Pollutants", the best-case scenario assumes a life of 60 years (a result driven by the useful life of infrastructure) across all introduced renewable infrastructure. This life of 60 years gives a best-case scenario of 1280880 MW y, and in contrast, a worst-case scenario assumes asset replacement after nine years (derived for utility-scale batteries) and 106285.5 MW y. The best-case scenario assumes the highest aggregation value from the third level analysis for materials, giving 1. The worst-case scenario assumes the lowest aggregation value from the third level analysis, giving 0. The third level analysis assumed a best-case scenario of 0 for no new projects going forward and a worst-case scenario of 50% more projects going forward. Therefore, a factor of 1.5 was applied to the greatest of each third level metric, being the worst-case figures.

TABLE 10: environmental second level metrics

	Data			Best		Worst		Normalised		
Metric	BAU	ALT1	ALT2	Value	Evidence	Value	Evidence	BAU	ALT1	ALT2
GHG Emissions (kt CO2 eq)	269692	183654	157240	5103	Coal generation to cease straight away (BAU)	270222	Coal generation to continue until 2030 at current rates (BAU)	0.002	0.327	0.426
Pollutants (MW y)	465065	816875	786775	1280880	All renewables lasting a 60-year lifecycle – transmission lines (based on ALT 2)	106286	All renewables lasting a 9-year lifecycle – Large-scale battery (based on BAU)	0.305	0.605	0.579
Materials	0.284	0.193	0.161	1	Highest Aggregation	0	Lowest Aggregatio n	0.284	0.193	0.161

The individual normalised results for each metric were then aggregated. Table 11 shows the relative weightings of each social performance metric, which are then aggregated to determine the social outcome for each of the three scenarios, as shown in Table 12.

TABLE 11: summary of derived weightings about each environmental metric derived from the results presented in appendix 1.

Environmental	GHG Emissions	0.49957
	Pollutants	0.26064
	Materials	0.23979

TABLE 12: final aggregated values about the environmental bottom line.

	BAU	ALT1	ALT2
Aggregation	0.05	0.12	0.13

From the results, the BAU has been exceeded, with the ALT2 transition proposal deemed as the best, closely followed by ALT1.

With the aggregated scores for each metric now identified, the first-level metrics' nBL assessment was performed, with the results detailed in the next section.

4.5 nBL analysis

Figure 1 provides a graphical interpretation of the results obtained for each bottom line in the form of a radar graph. Final aggregated values about each solution across all bottom lines are shown in Table 13. The radar graph shows each solution's score across all bottom lines. Note that ALT2 consumes the largest area of the three, which suggests it outperforms the other proposals.

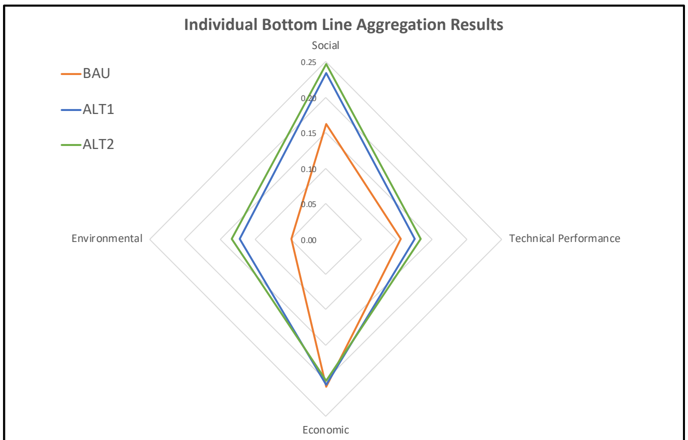

FIGURE 1: radar chart depicting the aggregated values for each solution across the four bottom lines.

TABLE 13: tabulation of the final aggregated values for each solution across all four bottom lines.

	Social	Technical Performance	Economic	Environmental
BAU	0.16	0.11	0.21	0.05
ALT1	0.23	0.13	0.21	0.12
ALT2	0.25	0.13	0.20	0.13

These values were then subject to Steps 3 and 4 of the nBL process. The weighting values attributed to each of the four bottom lines found through quantitative interview methods are shown in Table 14. Full results of the interview process from which bottom line weightings were derived are shown in Appendix J.

Table 14: Evaluation of weighting values to be applied in the aggregation process (Step 4).

	Weighting
Social	0.302
Technical Performance	0.187
Economic	0.318
Environmental	0.193

The aggregation process can occur now that each bottom line has a respective normalised value (shown in Table 13) and weight (shown in Table 14). Table 15 provides the final aggregated values for each solution and hence, the overall preferable option according to the nBL framework.

Table 15: Summary of final aggregated values for

	Aggregation
BAU	0.108
ALT1	0.130
ALT2	0.133

each solution.

Hence, ALT2 is the preferred solution according to the nBL framework.

5. Discussion

The results clarify the scenarios and identify risks. The evaluation of interviews was framed by the four bottom lines and compared with the nBL results. The results of each metric are discussed independently in Sections 5.1-5.5, with the discussion findings or each metric collated to identify the limitations of this research, opportunities to further this research and our final recommendations.

5.1 Technical Performance

Most energy experts interviewed thought that low conversion and transmission losses are not central to the energy transition's success. Hence, these two factors were weighted the lowest when calculating standardised metric values (see Appendix I). However, there was one exception to this point raised by interviewees. Improving the technical efficiencies of solar panels poses a big opportunity to the overall output of Victoria's renewable generation system. Residential solar panels have typical conversion rates of around 16%, with some conversion rates as high as 22%[33]. The conversion efficiency assumed for 2030 and applied in the nBL analysis was 30.70%[28].

In contrast, storage capacity and data transparency were considered the two integral technical factors of the four nominated metrics. While storage capacity is important, consumer data rules and data transparency are also important. The lack of access to data is a policy issue, thus presenting a bottleneck in accessing live usage data to identify potential improvements in the grid. Both Alternative 1 and 2 incorporate policy changes that eliminate this bottleneck.

The configuration of community microgrids and VPP's in urban areas will have a substantial role to play in balancing the grid system and providing vulnerable customers with excess energy to reduce their billed consumption. Also, prospects of community microgrids and VPP systems have strengthened since the introduction of the five-minute settlement by AEMO in October 2021. Five-minute settlement periods will effectively allow fast-response generators such as batteries to be more responsive to the current demand requirements of the grid system. AEMO has a leading role in facilitating the electricity market. It is the responsibility of AEMO to continue implementing regulations that optimise fast-response generators, such as the new spot price changes.

Outright storage capacity does not accurately represent a smart grid's ability to balance the load and provide security. The location of proposed storage locations was considered in the development of projects for both ALT1 and ALT2 scenarios. Throughout Victoria's renewable energy zones, projects were balanced to provide remote areas with grid reliability. On the other hand, the abilities of transformers and inverters were not considered in the technical performance analysis of the proposed grid systems (an area for further study).

5.2 Social

The social outcomes of the transition are of primary concern as there is a limit to expenditure that can be directed towards overarching environmental benefits. We found that employment is the most important aspect in measuring the energy transition's success (Table 14) with higher weighted importance than health and public satisfaction[37]. The nBL assessment predicted that the most jobs created were in the ALT2 solution, with 4610 jobs created per year between now and the year 2030. Jobs accounted for in each proposal consist of construction jobs and ongoing permanent jobs for operation. Whilst not considered for this analysis, additional employment will result through required accommodation and catering for workers and landscaping, fencing and other civil works.

People in the Latrobe Valley have no commitments of support after the closure of the remaining coal plants, but there is support for a social obligation moving forward. [8] Cozzi and Motherway (2021) show that if appropriate long-term planning is executed, most dislocated workers following coal plant closures will be able to find similar work moving forward in the transition.

The long-lasting physical health impacts for each of the three scenarios were estimated based on the impact of pollutants from Yallourn, Loy Yang A and Loy Yang B (Table 13). The BAU proposal has 37,046 persons affected, almost double that of the ALT2 scenario explained by Loy Yang A and Loy Yang B operating until 2030 for BAU. In contrast, the ALT2 proposal suggests this coal output is phased out as it is replaced with renewable energy. The results show that Victoria's ageing brown coal plants harm air quality, particularly in the Latrobe Valley. As outlined in the nBL assessment and reinforced by the Hazelwood Fire inquiry, the Latrobe Valley continues to suffer from increased death rates and a range of premature births, reduced lung function, cardiac impairments, and long-term cognitive decline[16].

While not directly measuring consumer engagement in the energy transition, the 'public satisfaction' metric was used for stakeholder management processes. We used for complaint data in the analysis highlighted matters raised by community members related to community engagement, planning processes and impacts to amenity[1]. The number of complaints related to various renewable infrastructure projects was calculated as 220, 220 and 320 for BAU, ALT1 and ALT2, respectively. The higher number of predicted complaints in ALT2 can be attributed to the high number of completed wind projects. The Victorian Government engaging in consultation with the public is of importance and will minimise dissonance and enhance the satisfaction of communities.

5.3 Economic cost

The economic costs from the transition are important. Economic insights gained from interviews were close to the results obtained in the nBL analysis. Unsurprisingly, the external costs of GHG emissions were highest for the BAU scenario, with a net present cost of US$29 billion by 2030. ALT1 and ALT2 cost US$19.7 billion and US$17 billion, respectively. External costs (environmental effects) were weighted as the most critical consideration in the economic metric

Furthermore, the capital costs of ALT2 were significantly higher than the other proposals due to its heavy investment in renewable infrastructure within the state borders, being three times the expenditure in the BAU case and almost double that of ALT1. However, the operational costs reveal that by 2030 the BAU and ALT2 cases will have a similar net present cost. By analysing the results of ALT2, we can see that coal at its current approximate generation costs $1 billion per year in Victoria (from our estimates), with the costs of all the new infrastructure in 2030 when coal is phased out costing the owners similar amounts. An important outcome of this research is that changing from coal to renewables would not increase electricity prices.

ALT1 shows significantly higher operating costs of 1.7 times the other two alternatives. This higher cost for ALT1 is primarily due to the substantial amounts of expensive imported energy. However, the operational costs metric was weighted the lowest because interviewees argued that operational costs for renewables are in a state of steep decline.

As can be seen, the results have shown us that external GHG costs disfavour the BAU, capital costs disfavour ALT2, and operational costs disfavour ALT. These significant differences between the metrics for each alternative, combined with each metric's importance weighting, led to all alternatives coming out with aggregated scores of 0.21 for BAU and ALT1 and 0.2 for ALT2, which are close. The most critical point from these results is that rapid phasing out of coal is economically feasible. Furthermore, with the large variability in the social cost of carbon, coupled with its inevitable increase as the effects of climate change increase, the costs difference between the alternatives is likely to be even more pronounced and favour ALT1 and ALT2. This favouring of ALT1 and ALT2 would be especially true between 2030 and 2050, where their emissions would be close to zero, with the BAU continuing its heavy emission generation.

There likely exists an optimal "in-between" solution between ALT1 and ALT2. As we have analysed the two extremes of reliance on importation and self-sustaining infrastructure, and both have achieved similar scores, the combination of the two will optimise costs in Victoria's energy transition. By incorporating parts of the interstate energy importation proposals presented in ALT1 into the proposal for ALT2, there exists an opportunity to harness the resources from interstate, allowing the reduction in capital expenditure present in ALT2 while also reducing the operating expenditure present in ALT1.

Therefore, through smart importation planning, the optimum cost can be achieved by sometimes being self-reliant and sometimes importing. Unfortunately, the difference in renewable targets, political parties, and political agendas between the states is likely to prove problematic in achieving good inter-state collaboration.

5.4 Environmental

The environmental bottom line showed GHG emissions being the most important, and we weighted this as an important metric. GHG emissions accounted for 50% of the environmental bottom line. Before aggregating the results from the normalised data, the BAU accounted for only 0.002, while the alternative accounted for 0.426. This difference in the weightings showed the greatest variance in comparing normalised data between proposed solutions, stressing the importance of GHG emissions in the energy industry. The interview results aligned with our environmental analysis, which sees Victoria rapidly building a self-sustainable renewable future as the optimal solution from the assessment (ALT2). Also, 90% of interviewees answered 3/7 or greater when asked about the importance of the construction of renewable infrastructure in Victoria.

We quantified the impacts of renewable infrastructure material components with some limitations. For example, large batteries' construction materials have focused on the lithium-ion component and did not include other components such as aluminium or steel framing because they are not listed in the available renewable energy infrastructure materials analysis[20].

A significant amount of concrete is needed to implement the renewable infrastructure[20], particularly wind turbines, where concrete foundations for onshore turbines require 937,500kg/MW. Hence, our model assumes 1963.60 kt of concrete for BAU and ALT1 and 6,169.69 kt for ALT2. The ALT2 solution assumes constant concrete requirements for both onshore and offshore applications. ALT2 assumes 63.74% of renewable capacity is contributed from offshore wind, and this would require even more of the material for foundations.

Although ALT1 falls short of ALT2, building interconnector lines to transmit energy between states is still important, and the energy experts we interviewed supported this importance. Incorporating interconnector lines would be optimum in the final solution. The feedback from interviewees was that we cannot be limited to Victorian resources and need to take a "what if" approach going forward. The current proposal only looks at 2,233km of new transmission lines adopted into the system new infrastructure. Looking forward, it would be much more of interest to Victoria and Australia to have more interconnector lines. If this was adopted into ALT2 in the materials sub-metrics, the ALT2 aggregation plummets from 0.161 to 0.111. Although the transmission lines in the third level metrics only consider distance (km), other additions of GHG Emissions will come from the implementations of such infrastructure. These transmission lines contribute an additional 2378.46 kt CO_2 eq and provide an additional 75840 MW y to the LCA (Life Cycle

Assessment) because of 1,264 MW from the transmission infrastructure. The consequence of the transmission line GHG Emissions significantly alters the outcomes in the second-level analysis. The overall aggregation for ALT2 and ALT1 stay at 0.13 and 0.12 when incorporating such a change.

Our research concludes that constructing renewable infrastructure in Victoria to decrease GHG Emissions is important. The rapid introduction of renewable infrastructure within Victoria allows for a faster decommissioning of coal generation while keeping Victoria powered. There is an environmental optimum within the BAU, as no new materials are needed to build such an energy system. Further study regarding the environmental impacts could look further into the total quantity of materials needed (instead of just the critical material).

5.5 Limits to the research and Future Research

Firstly, as discussed previously, construction costs associated with renewable projects is likely to decline and was not considered in the analysis. It may further increase the viability of the ALT2 above other solutions. Secondly, this study has considered each proposal until 2030 to assess its viability. Since the BAU case will continue fossil energy production until 2050, the costs associated with its emissions and the investment in renewables should be considered. It will be required in any case over those 20 years. The reducing costs of renewables may favour the BAU case as it will invest more in technological advances and improve BAU in terms of cost. However, the cost of carbon will also increase, making for a viable point of comparison and further research.

Interventions such as implementing Carbon Capture and Storage (CCS) (including sequestration of carbon at coal plants) were not considered solutions. Including CCS would create significant savings in GHG emission costs. However, it would increase generation costs at coal plants and negatively affect the BAU solution. CCS in Gippsland would bring an annual economic benefit of $896m, 2,707 jobs during construction, and 1,176 annual jobs after construction[11] .

Similarly, the economic benefits of each case were not considered. This research has established that the costs of each alternative are similar in 2030. However, there are opportunities for extra economic benefit from the transition that could be considered. The complex nature of smart grid technologies, such as batteries, also proved difficult to analyse from technical and environmental perspectives.

This analysis focused solely on energy storage as the predominant smart intervention to eliminate reverse voltage effects and shifting load. However, as one interviewee noted, inverters, transformers and storage will all provide beneficial outcomes depending on the location and composition of the local electricity network. The introduction of tools to measure the impacts of inverters and transformers in a smart grid system would provide another pathway to measuring the reliability of a grid system. Additionally, developing further insight into the material compositions of smart technologies is another avenue for further research. As discussed in Section 5.4, the material composition of new batteries was simplified to the lithium-ion battery instead of a more comprehensive analysis considering the full range of materials used.

Additionally, there is a further need to investigate material deposits on a state and national level. Renewable projects require unique materials. Insufficient reserves could lead to a need for dependencies on foreign markets and contribute to additional CO_2 emissions from importing and refining material. This need for special materials for renewables also impacts the economic analysis in greater upfront costs to build potential renewable projects. The absence of data required to undertake comprehensive analysis was an issue for the environmental bottom line and was indicative of a larger issue within the methodology.

6. Conclusion and Recommendations

The purpose of this analysis was to determine a clear plan for Victoria to adopt in pursuit of net-zero emissions by 2050. By applying a multi-criteria framework in the year 2030. ALT2 produced the best outcome of the three scenarios (Section 4.5), followed closely by ALT1. However, this is not to say that Victoria should pursue a renewable generation capacity capable of supplying 100% of the peak demand. As mentioned in the discussion, the optimum design is to increase renewable generation and increase transmission capacity for electricity import.

The economic and social discussion revealed that Victoria's path forward is through rapid phasing out of coal by 2030, following the path of ALT2, which involves installing a large capacity of renewable infrastructure, however incorporating part of the ALT1 solution to develop a smart interstate network. As discussed in Section 5.3, this will allow Victoria to achieve an optimal price point between ALT1 and ALT2. Its expected imports can reduce the capital expenditure of an entirely self-sufficient Victoria while avoiding the significant annual costs associated with energy imports. Furthermore, as discussed in Section 5.4, installing renewable infrastructure within Victoria to build a self-sufficient system while still delivering interconnecting networks will enhance material efficiencies within Australia. As discussed in Sections 5.3 and 5.4, it would also assist the rapid phase-out of coal-based generation by 2030. The wholistic economic cost of doing so is no more expensive than continuing at the current BAU trajectory as detailed in the economic analysis of the three scenarios.

Reductions in GHG emissions will help the health and well-being of the Earth and society and reduce GHG externality costs. While we recommend an optimal point between the two alternative solutions, other factors must be incorporated to place Victoria in a promising position to meet net-zero emissions by 2050.

There are policy and regulation changes that the Victorian State Government can implement to improve social acceptance of the energy transition and promote grid improvement. The Victorian State Government plays a vital role in the energy transition. To combat the absence of a clear plan to transition away from fossil-fuel-based industries, the Victorian Government must implement a transition campaign strategy for workers, contractors, and families in the Latrobe Valley. As discussed in Section 5.2, skills needed in the coal industry are transferrable to the renewable industry. Establishing access to training and counsel for local Latrobe Valley workers will support the region's long-term economic and social prosperity, making the area attractive for new employers and industries to enter the region.

Additionally, discussion points in Section 5.1 outline the need for the Victorian Government to enforce a distribution market that promotes innovation through access to smart meter data. In this recommendation, the government will assume ownership of the smart meter data and enforce regulations that limit data control among stakeholders such as distribution businesses and gen-tailers. Policy changes made by the Victorian Government will need to be supported by other key industry stakeholders such as AEMO.

Section 5.2 shows the lessons from the failures of the recently closed Hazelwood plant. For the 2028 closure of Yallourn the owner should properly rehabilitating the mine area to avoid risks of collapse or fire in the future and converting the space for community use.

Discussion and analysis of each solution's results within the *n*BL framework has made holistic recommendations across social, technical performance, economic and environmental bottom lines. These recommendations were to improve the overall score of the transition according to the assessment framework used. Since the assessment method was created with the overarching criteria of net-zero emissions by 2050, implementation of these recommendations will place Victoria in a promising position to achieve this goal.

7. Data Availability

Datasets and appendices related to this article can be requested from the Author.

8. Statements and Declaration

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