

Economically viable emissions reductions through industrial microgrid optimisation

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Abstract

The optimisation of systems where engaging with a high volume of data is a critical task in engineering and information technology. This paper explores the use of optimisation tool in energy systems, that can be utilised in combination with the optimisation of communication systems. This paper examines the environmental impact of implementing economically competitive microgrids in industrial projects and offers a range of microgrid configurations that display notable environmental improvements when compared to the benchmark. This benchmark is a proposed AU\$31.1m substation infrastructure upgrade to supply a hypothetical 60 MW industrial load through the centralised electricity network in Western Australia. With the assistance of HOMER (Hybrid Optimisation of Multiple Energy Resources) modelling software and industry data, a range of distributed energy resource configurations were modelled over a 25-year project life. Evaluations found that across economically viable topologies, an average reduction of 52% on CO₂ gas emissions was observed. Mean initial capital expenses for featured microgrid systems were observed to be more than 6 times the benchmark, however mean emissions reductions were observed at 439.76 T/yr for every dollar invested. A set of featured architectures are presented utilizing combined heat and power equipped gas turbine, diesel generator, wind farm and vanadium redox flow battery bank.

Keywords: Microgrid, distributed energy resources, optimisation, sensitivity analysis, cost-effectiveness analysis, net present cost, levelised cost of energy, combined heat and power

1. Introduction

Electricity consumer expectations have gone beyond that of reliability and security and now include reduced environmental impact and improved social benefits [1]. Of great importance to the Australian energy market is the initiative to reach the national emissions targets, which aims to reduce greenhouse gas (GHG) emissions 20 % by 2020 (from 2005 GHG levels) [2, 3]. The International Energy Agency has predicted that at current trajectory with no significant policy changes, fossil fuels will still account for approximately 90 % of world energy production in that time [4]. The dissemination of microgrid technology in industrial land development and construction will provide a significant boost to these efforts.

Energy market conditions, coupled with the rising use of DERs, provide a unique opportunity for increased renewable penetration and disruptive technology uptake in industrial area development to offset overhead costs [5, 6]. These factors are giving rise to the smart grid concept, which is an electrical network that, among other things, facilitates an intelligent integration of DERs [7]. Deeper still are microgrids, which serve as the building blocks of the larger, more encompassing smart grids [7]. Microgrids are designed to address a multi-objective purpose, which includes enhanced reliability,

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increased renewable DER use and improved efficiencies through waste heat recovery [8]. The microgrid concept is beginning to form a large part of the Australian Renewable Energy Agency (ARENA) strategy to address renewable energy targets [9]. The optimisation of systems in electrical engineering and information technology is very critical to reduce total cost investment and operation, and consequently for end-users [10, 11]. The optimisation algorithms and tools on energy systems are required to include communication systems in near future to enable decision makers to decide on the optimisation of investment cost of such systems. Communication system is essential for energy systems to collect and manage data, control the system, estimate the working state [12], and optimise the operational costs.

In 2016 the development plan for the Onslow DER microgrid was announced [13]. The project is the largest DER project in Australia with the aim to meet 50% of Onslow's electricity needs through renewable sources and serves as a precedent for renewable penetration into residential and industrial zones. Although the Onslow project will act as a useful prototype of large-scale DER use, there is still a need to research ways of improving the investment profitability and clarifying the specific environmental benefits of microgrids in Australian industrial settings. Microgrid configurations that can facilitate major GHG reductions at a feasible investment expense would serve to promote more widespread dissemination of the concept among land developers. As ageing infrastructure reaches its limits, significant decisions loom over the next evolution of electrical distribution networks in Australia.

2. Considered Industrial Load

The Nambeelup Industrial Area (NIA), located approximately 9 km northeast of the city of Mandurah in Western Australia, is the hypothetical electrical and thermal load considered for this task (refer to Fig. 1). Currently, the NIA is an undeveloped parcel of land under the ownership of the Western Australian State Government land development agency, Landcorp. However, development plans are underway to build a large industrial business park on the land which would carry a peak electrical load of 60 MW and a peak thermal load of 30.5 MW. The region is currently supplied by a single 22kV (324 A rated) feeder originating from the Meadow Springs Substation (MSS), which is part of the South West Interconnected System (SWIS). According to recent utility reports there is only 5 MVA of remaining capacity available through the MSS [14].

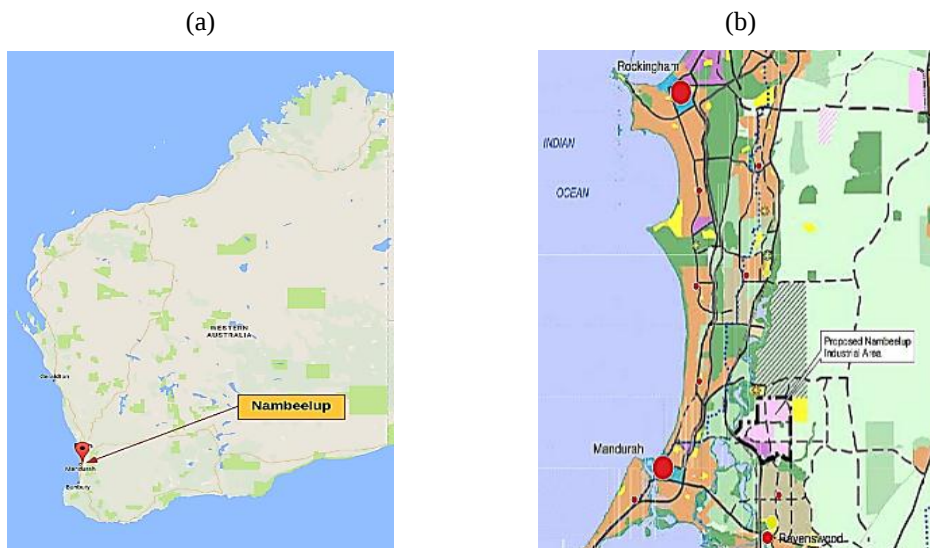


Fig. 1. (a) Nambeelup Location State Level, (b) NIA specific location

For large commercial or industrial operations, the primary electricity retailer, Synergy, offers a range of tariff options. For this study the Time of Use (ToU) business rate was used, details are in Table 1.

Table 1. Network electricity tariff details

<i>Tariff Type</i>	<i>Averaged Cost per kWh</i>	<i>NIA Annual Usage (GWh)</i>	<i>Annual Cost (\$M)</i>
<i>Time of Use [15]</i>	0.3337	210.12	70.12

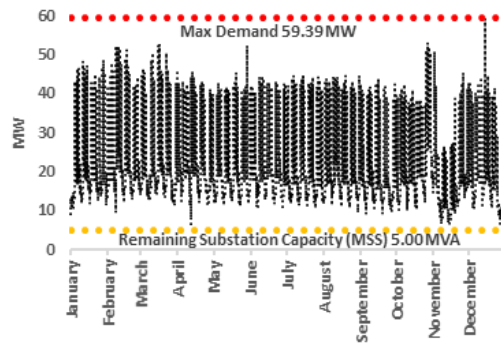
Solar conditions are generally consistent with other major Australian cities with a relative Global Horizontal Irradiance (GHI) spike during the summer months and an average GHI of 5.51 kWh/m²/day. Wind conditions are relatively better relative to other major urban areas with an annual average wind velocity of 7.48 m/s measured at a height of 50 m.

Energy usage data of a comparable business park in 2016 was obtained from Landcorp which was used to generate a hypothetical load profile for the NIA. A pattern of higher usage during the business hours is evident when looking at the hourly average electrical loads over the whole year. This pattern is consistent with typical industrial and commercial usage patterns (see Fig. 2(a)). As this study will also include an analysis on meeting thermal demands a thermal load was modelled. Using concepts from a 2008 Department of Industry, Innovation and Science report [16] the trends in fuel energy consumption per household show an electricity to gas use ratio of approximately 25:17. The thermal scope has been limited to very traditional heating and cooking delivery types using natural gas as the primary fuel. Using this ratio to produce an assumption for the NIA thermal load gives an annual gas (Thermal) consumption – 142.8 GWh (30.5 MW peak) (see Fig. 2(b)). The conventional generation models will include options for CHP as part of the value analysis based on the assumed thermal load.

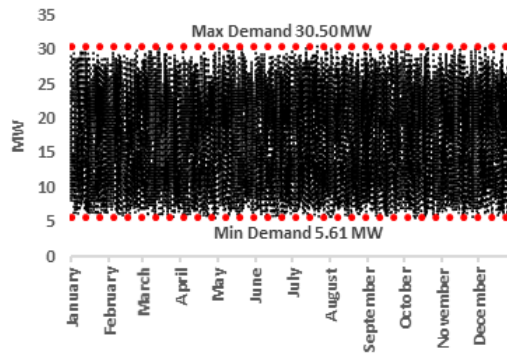
3. Considered Microgrid Configurations

The component scope was developed based on a thorough literature review and refined using HOMER modelling software. The initial considered configuration included various technologies from conventional generation, renewable generation and energy storage devices. After a refining process the final system includes allowed components (subject to each permutation) as listed below [17-19].

- I. Centralised Grid Connection
 - a) Proposed infrastructure upgrade of the MSS providing a revised capacity of 70 MVA
- II. Conventional Electrical Generation
 - a) Diesel Reciprocating Internal Combustion Engine (RICE) rated to 5 MVA
 - b) Natural Gas-fired Combustion Turbine (CT) rated to 32 MVA
- III. Renewable Electrical Generation
 - a) Solar Photovoltaic Polycrystalline-Silicon (Poly-Si) fixed Flat Plate (scalable to any size)
 - b) Large Wind Turbine rated to 1.65 MW
- IV. Battery Electrical Energy Storage
 - a) Lead-Acid batteries rated to 4.92 kWh each
 - b) Lithium-Ion batteries rated to 13.5 kWh each
 - c) Vanadium Redox Flow batteries rated to 400 kWh each
- V. Thermal Generation
 - a) Traditional Gas Boiler attached to the natural gas network
 - b) CHP waste heat recovery from gas-fired CT



(a)



(b)

Fig. 2. (a) NIA Yearly Electrical Load Profile (MW), (b) NIA Yearly Thermal Load Profile (MW)

HOMER was used to produce many possible permutations of the allowable components. Modelled microgrid systems were then compared against a benchmark scenario which involves a \$31.1M infrastructure upgrade to the MSS. See Fig. 3 for a diagram of the considered technologies.

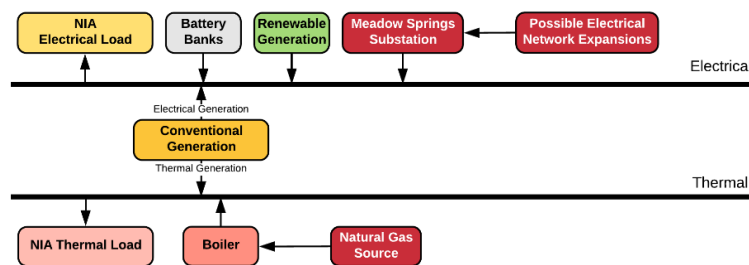


Fig. 3. Schematic of proposed microgrid system components

3.1. Study Methodology and Objective

The testing begins with defining economic viability. This was said to be any model permutation that produces a project net present cost (NPC) that is less than the benchmark NPC. Within the scope of economically viable systems, a nested analysis would then be conducted on the CO₂ emissions attributes of the system. Finally, a requirement of any microgrid system is the ability to run autonomously (islanded) from the centralised grid. As part of the objective an examination into the system autonomy was conducted to ensure sufficient energy storage autonomy to allow for the proposed microgrid to operate

islanded [20]. The microgrid permutation optimisation function to find the most economically viable emissions reduction is defined within equation 1.

$$\begin{aligned} \text{Objective} &= \min \left(\sum_{i=1}^G \mu_{ei} E_i \right) \\ \text{Constraints: } &\begin{cases} NPC_{mg} < NPC_{BM} \\ Cap_b \geq 24 \text{ MWh} \\ \text{No Stability Concerns} \end{cases} \end{aligned} \quad (1)$$

where:

- μ_{ei} is the CO₂ emissions intensity in T/MWh of generator i ;
- E_i is the electrical energy production in MWh from generator i ;
- NPC_{mg} is the total project net present cost in \$M of the proposed microgrid system;
- NPC_{BM} is the total project net present cost in \$M of the benchmark system;
- Cap_b is the energy storage capacity in MWh of the battery bank;
- G is the number of generation sources.

3.2. Model inputs

Table 2-5 provides details on environmental and economic inputs. Note that the power electronic converter assumptions were \$700 per kW (capital and replacement) with an O&M cost of \$6 per MWh and a lifetime of 15 years. Diesel was assumed to be \$1.20 per liter while natural gas was assumed to cost \$0.125 per cubic meter [21, 22].

Table 2. Emissions inputs

Generation Source	CO ₂ Emissions Intensity*	Reference
SWIS	0.700	[23]
Diesel RICE	0.870	[23]
Natural Gas CT	0.640	[23]

*: Defined as the mass of carbon dioxide gas emissions per unit of electricity generated and sent to the end user. Expressed in T/MWh.

Table 3. Conventional generation economic inputs

Fuel	Diesel	Natural Gas	Natural Gas
Model Type	CAT C175-20 Prime (5 MVA Rated)	General Electric TM2500 (32 MVA Rated)	General Electric TM2500 (32 MVA Rated)
CHP	No	No	Yes
Capital Costs (\$/kW)	1717.76	1564.2	1941.1
Replacement Costs (\$/kW)	1370.88	1224	1315.6
Non-Fuel O&M Costs (\$/kW-hr)	0.0125	0.0070	0.0070
Fuel Curve (Slope/Intercept)	0.1583x+0.0414 L/hr/kW	0.1723x+0.0568 m3/hr/kW	0.1723x+0.0568 m3/hr/kW
Operating Hours (hrs)	72000	100000	100000

Table 4. Renewable generation economic inputs

Type	Solar PV (fixed)	Wind Turbine
Model Type	Generic Poly-Si Flat Plate	Vestas V82 (1.65 MW Rated)
Capital Costs (\$/kW)	2000	2180.1
Replacement Costs (\$/kW)	1900	1638.9
O&M Costs (\$/kW-hr)	0.0027	0.0075
Lifetime (yrs)	25	22

Table 5. Battery energy storage economic inputs

Type	Lead-Acid	Lithium-Ion	Vanadium Redox Flow
Model Type	Generic – based on Surrette - 6 CS 25P (4.92 kWh Rated)	Generic – based on LGChem LG RESU 10 (13.5 kWh Rated)	Generic – based on Gildemeister Cellcube FB 200-400 (400 kWh Rated)
Capital Costs (\$/Unit)	1600	8000	145776
Replacement Costs (\$/Unit)	1600	3033.7	89887.64
O&M Costs (\$/Unit-yr)	15	8.33	10204
Throughput (MWh)	10	37.8	8670
Lifetime (yrs)	11.2	15	20

4. Analysis Results

The HOMER optimisation model produced over 4000 permutations using the component limitations and model inputs as outlined in this paper. The benchmark system had an initial capital requirement of \$31.1M and an overall project NPC of \$1.13B. Under this scenario there was an average of 182.15 kT/yr of CO₂ emissions. As a general observation, where renewable DER, cogeneration or battery usage was used increasingly, there was a notable reduction of CO₂ emissions produced while meeting the NIA demand (see Fig. 4). HOMER permutations were regularly able to reduce emissions to below the grid-only benchmark of 182.15 kT/yr. Furthermore, over 75 % of topology permutations produced systems that were under the required emissions cap of 142.3 kT/yr to meet the 2030 Australian Climate Change Target (if applied to the NIA as a microcosm of the wider national GHG producers) [24]. In order to capture all possibilities in energy systems, HOMER is evaluating the search space thoroughly to provide a complete statistical analysis, other using heuristic optimisation to find only the final solution [25].

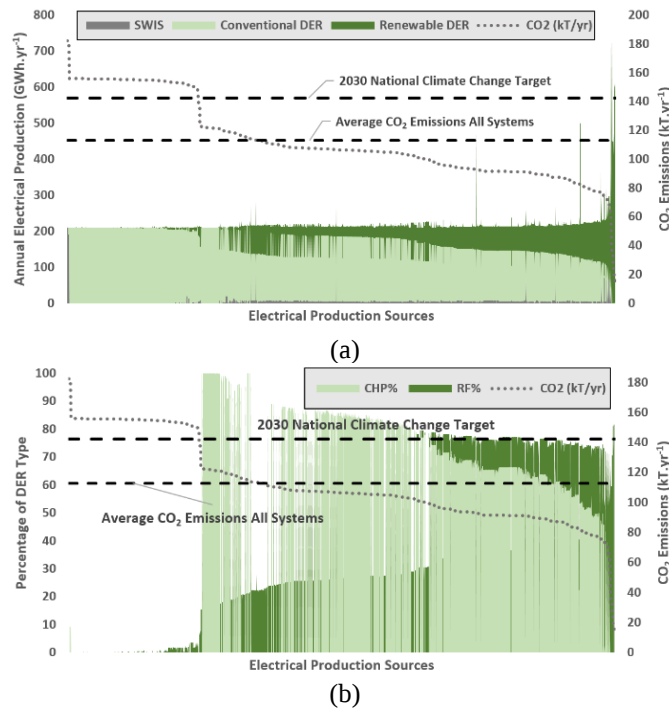


Fig. 4. (a) Emissions Metrics by Generation Type, (b) Renewable Emissions Reduction Comparison to CHP

Table 6. Featured system configurations

ID	Configuration (Available Capacity)	Project NPC (\$M)	CO ₂ Emissions (kT/yr)
0 (BM)	Grid (70 MW)	1127.28	182.15
1	PV (24 MW), WT (24.75 MW) GT(chp) (32 MVA), VRFB (80 MWh) Pconv (32 MW)	396.24	70.51
2	PV (26.6 MW), WT (23.1 MW) GT (32 MVA), VRFB (79.6 MWh) Pconv (35 MW)	403.43	87.22
3	PV (43 MW), GT (32 MVA) DG (5 MVA), VRFB (60.4 MWh) Pconv (31.3 MW)	410.24	115.63
4	WT (39.6 MW), GT(chp) (32 MVA) DG (5 MVA), VRFB (127.6 MWh) Pconv (20.2 MW)	455.27	65.37
5	PV (102.3 MW), DG (5 MVA) LI (107.8 MWh), Grid (70 MW) Pconv (41.6 MW)	706.64	93.90

Abbreviations: BM – Benchmark, PV – Photovoltaic, WT – Wind Turbine, GT – Gas Turbine, VRFB – Vanadium Redox Flow Battery, PConv – Power Converter, DG – Diesel Generator, LI – Lithium Ion Battery

Table 6 provides a selection of the best performing microgrid system configurations that meet all the objective criteria as outlined in (1). It is immediately evident that scenarios involving DER carry a higher initial capital requirement compared to the benchmark. However, this is offset greatly in terms of project NPC with an observed reduction across presented systems. As seen, all configurations 1 to 5 have less NPC compared to the benchmark. These feature systems all exhibit dramatic reductions in CO₂ emissions with an observed reduction range of 36.52 – 64.11 %. From featured systems it is also evident that the largest reductions occur in systems that have a CHP equipped generator (systems 1 and 4). Also, it is shown that the NPC of system 1 has the least NPC amongst all configurations with about 1/3 of NPC of the benchmark. Fig. 5 provides a performance summary of featured systems relative to the benchmark. From the perspective of best cost effectiveness in emissions reduction, system 4 shows the most promise with a 536.42 T/yr reduction per dollar invested. In this system, the largest components within the NPC tend to be the initial expenses. Fuel costs and O&M costs such as tariffs are reduced or removed completely which significantly lowers ongoing project costs. Therefore, regarding the emissions reduction, system 4 is more viable compared to others. The benchmark shows inverted behaviour in that the initial expenses are relatively low, but ongoing costs are vastly larger. Furthermore, by putting a cost to performance indicators such as emissions, it is evident the impact of poor performance in these categories.

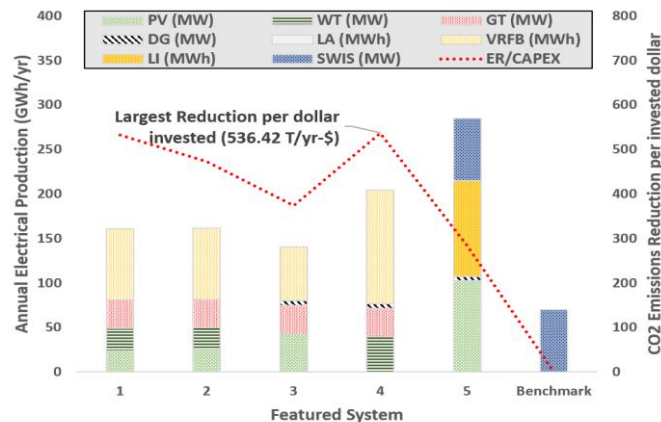


Fig. 5. Featured System Attributes, Annual Electrical Production (left axis), CO₂ Emissions Reduction per Capital Expense (right axis)

Performing a sensitivity analysis on key attributes of that large scale industrial microgrid, such as wind turbine, battery and prices, shows that system with diverse generation sources are less vulnerable to significant system cost variation.

Finally, it was noted that Vanadium Redox Flow Batteries (VRFB) featured in the best performing systems. The only featured system to not use VRFB technology was system 5 and it was noted that grid reliance was heavier in that instance. From observation this seems to be explained by the significantly lower Battery Wear Cost (\$/kWh) and Energy Cost (\$/kWh) enjoyed by the VRFB relative to the other technologies. This leads the dispatch controller to prefer this technology and increase VRFB throughput, making it very economical at the same time as supporting emissions reducing technologies. See Fig. 6 below for the battery energy costs observed over the 12-month period.

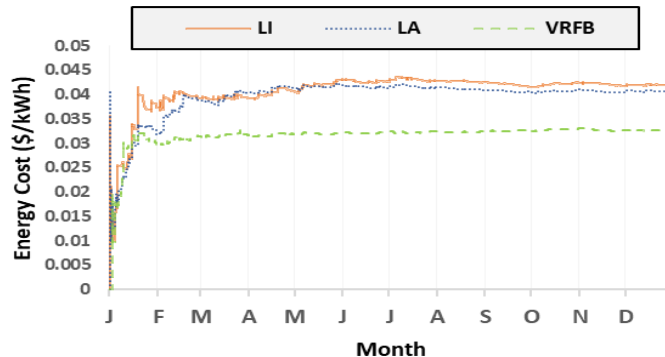


Fig. 6. Battery energy cost (\$/kWh)

5. Conclusion

This study has explored the microgrid concept as it is applied to a Western Australian industrial development. The objective was to find and examine economically feasible configurations that provide an environmentally improved option when compared to a simple network upgrade and connection. A microgrid system containing a variety of conventional, renewable and energy storage sources was considered and optimised using HOMER software. Results of this study has shown that the application of hybrid DER to a 60 MW industrial load leads to significant emissions reductions and improved project NPC at the cost of elevated initial capital costs. Finally, a single system (4) was presented as a preferred system that provides a 536.42 tonne per year CO₂ emissions reduction for every dollar invested with an NPC 60 % less than the benchmark. Although the initial investment costs for this system is higher but the operation costs including fuel costs and tariff along with emission cost are reduced significantly. Therefore, the use of renewable energy and CHP in large industrial parks results in the project net present costs are on average 2 times less than the centralised electricity network solution.

Future works include the details modelling and analysis of reliability evaluation and the associated cost into the system. Also, development of integrated optimisation algorithm for energy and communication system would be another research topic in future.

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