School of Civil and Mechanical Engineering

Comparative Sustainability Assessment of Decentralised Power Supply Systems in Remote Areas

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Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree of diploma in any university.

Signature: ______________________________

Date: ______________________________

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Abstract

Electricity is not only an essential commodity to power the modern economy but it also has environmental implications. The electricity sector alone accounts for 35% of Australia's greenhouse gas emissions and contributes to other significant impacts such as loss of biodiversity and ecotoxicities. The remote area power supply (RAPS) in Australia is the fastest growing contributor to these impacts due to rapid increase of remote mining projects that rely heavily on fossil fuels. In Western Australia, electricity demand in remote areas is expected to increase by 3,617 GWh, which will result in the annual emission of 2.2 Mt CO_2 eq. The use of renewable energy technologies (RETs) has a potential to mitigate environmental impacts, but the cost of the integration to RAPS systems and low dispatch rates slowed down the penetration of RETs. Diversification of energy sources through renewable-fossil fuel hybrid system has been found to address the technical and economic concerns. In Western Australia, distribution utilities in remote areas still favour diesel power stations due to high capital cost. Consideration of economic aspect alone is not enough to address the RET challenges in RAPS. Eco-efficiency analysis (EEA), which integrates both economics and environment from a life cycle perspective has a potential for identification of strategies to deliver environmentally friendly electricity in a cost-effective manner.

The integration of these two pillars of sustainability has not been considered yet to achieve improvement in the eco-efficiency performance of RAPS in Western Australia. Considering the expansion of remote mining projects and associated electricity demand requirement in Western Australia, a comprehensive EEA framework has been developed to discern the eco-efficiency of RAPS systems. This framework integrates environmental life cycle assessment (ELCA), life cycle costing (LCC), eco-efficiency strategies and eco-efficiency portfolio analysis. The development of this framework assisted in the selection of eco-efficient RAPS options that contribute to the reduction in environmental impacts while generating electricity at a reasonable cost.

In this research, two solar PV-diesel hybrid systems in Marble Bar and Yungngora and a wind-diesel hybrid system in Coral Bay were investigated as these represent existing RAPS systems in Western Australia. The operational characteristics of the hybrid systems were simulated using HOMER software. The energy and material inputs were used to develop a life cycle inventory and these were entered in SimaPro software to identify

environmental hotspots. Eco-efficiency strategies were implemented to treat the identified hotspots in order to reduce the environmental impacts. The improvement of diesel engine operation, integration of exhaust gas recirculation, installation of rooftop solar PV on residential houses and expansion of renewable energy capacity were found to be relevant strategies for the hybrid systems in Western Australia. A follow up ELCA was conducted to evaluate the potential environmental improvement of the improved RAPS options. The economic performance of the improved RAPS options was assessed using LCC to evaluate the cost-effectiveness of these options. However, it is difficult to select a single option using the ELCA and LLC results as some options are more environmentally friendly but expensive or vice versa. Therefore, the ELCA and LCC results of both existing and improved RAPS options were normalised for portfolio analysis to assist in the selection of eco-efficient RAPS options considering both environmental and economic factors.

The options MB8 (incorporation of the improved diesel engine operation, integrated EGR and expanded renewable energy capacity to 450 kW_p), Yg17 (incorporation of improved diesel engine operation, integrated EGR, installed rooftop solar PV on residential houses (207 kW_p) and expanded renewable energy capacity to 400 kW_p), CB6 (incorporation of improved diesel engine operation, integrated EGR and installed rooftop solar PV on residential houses (147 kW_p)) for the hybrid systems in Marble Bar, Yungngora and Coral Bay, respectively were found to be eco-efficient RAPS options due to lower environmental impact and significant cost savings potential. Finally, the integrated eco-efficiency and life cycle management concept can help Western Australian off-grid power distribution utilities to improve the eco-efficiency of the expanding remote area power supply.

List of Publications

Journal Publication

Arceo, A., Rosano, M., & Biswas, W. K. (2017). Eco-efficiency analysis for remote area power supply selection in Western Australia. *Clean Technologies and Environmental Policy*. doi:10.1007/s10098-017-1438-6

Conference Proceedings

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List of Abbreviations

1,4-DB eq	1,4 Dichlorobenzene Equivalent
ACLA	Attributional Life Cycle Assessment
AER	Australian Energy Regulator
AEMO	Australian Energy Market Operator
AHP	Analytical Hierarchy Process
ARENA	Australian Renewable Energy Agency
AUD	Australian Dollar
AusLCI	Australian Unit Process LCI
BOM	Bureau of Meteorology
BPIC	Building Products Innovation Council
BREE	Bureau of Resources and Energy Economics
CdTe	Cadmium Telluride
CFC-11 eq	Chlorofluorocarbon Equivalent
CLCA	Consequential Life Cycle Assessment
CO_2 eq	Carbon Dioxide Equivalent
DOD	Depth of Discharge
DOE	Department of Environment
EEA	Eco-Efficiency Analysis
EGR	Exhaust Gas Recirculation
ELCA	Environmental Life Cycle Assessment
EPBT	Energy Pay Back Time
FiT	Feed-in Tariff
FU	Functional Unit
GDEI	Gross Domestic Environmental Impact

GDP	Gross Domestic Product
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
IRE	Installed Renewable Energy
ISO	International Organisation for Standardisation
kbq	Kilo Becquerel
kWh	Kilowatt Hour
kW_p	Kilowatt Peak
LCC	Life Cycle Costing
LCEI	Life Cycle Environmental Impact
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelised Cost of Electricity
LCSA	Life Cycle Sustainability Assessment
LR	Load Restriction
MCDA	Multi-Criteria Decision Analysis
MJ	Mega Joule
Mono-Si	Monocrystalline Silicon
MRET	Mandatory Renewable Energy Target
Multi-Si	Multicrystalline Silicon
MWh	Mega Watt hour
N_2O	Nitrous Oxide
NMVOC	Non-Methane Volatile Organic Compound
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NV	Normalised Value

NWIS	North West Interconnected System
$PM_{2.5}$ eq	Particulate Matter Equivalent
PO_4 eq	Phosphate Equivalent
PV	Photovoltaic
RAPS	Remote Area Power Supply
RET	Renewable Energy Technology
RSI	Relative Sustainability Index
RSPV	Rooftop Solar Photovoltaic
SAS	Stand Alone Systems
Sb eq	Antimony equivalent
SETAC	Society of Environmental Toxicology and Chemistry
SLCA	Social Life Cycle Assessment
SO_2 eq	Sulfuric Acid Equivalent
SSES	Solar Smoothing Energy Storage
SWIS	South West Interconnected System
TBL	Triple Bottom Line
U235 eq	Uranium-235 Equivalent
UNEP	United Nations Environment Programme
WBCSD	World Business Council for Sustainable Development
WF	Weighting Factor

Chapter 1
Introduction

This thesis assesses the eco-efficiency performance of existing renewable and non-renewable technologies used in remote area power supply (RAPS) in Western Australia and proposes future eco-efficient power supply options to generate electricity in an environmentally friendly and cost-effective manner.

1.1 Background of the Study

An important implication of sustainable development is the economic supply of clean energy that has no undesirable societal and environmental impacts (Kaygusuz & Kaygusuz, 2002). The use of sustainable energy can potentially contribute to sustainable development goals as it addresses existing concerns with global resource scarcity by conserving energy for future generations (Riesz, Hindsberger, Gilmore, & Riedy, 2014; Tester, Drake, Driscoll, Golay, & Peters, 2005). Sustainable energy ensures the use of clean resources to mitigate large quantities of anthropogenic greenhouse gas (GHG) emissions in order to reduce unprecedented rises in global temperature, which could detrimentally disrupt ecosystems and sea level rise (Boyle, Everett, & Ramage, 2003).

Whilst the sustainable energy development strategy considers environmental conservation, economic prosperity and social equity, countries such as Australia mainly focuses only on delivering energy with the best cost performance (Evans & Peck, 2011). The power distribution utilities of most remote area power supply (RAPS) systems in Australia generate electricity from diesel and gas fuels since the per unit capital costs of these technologies are low (ARENA, 2014). But in recent years, environmental degradation, scarcity of fossil fuels and electricity market legislation including feed-in-tariffs (FiT) and environmental taxation have led to the extensive utilisation of renewable energy technologies (RETs) (IRENA & GWEC, 2012).

In Australia, most energy planners and developers for RAPS systems prefer conventional gas and diesel technologies because of the cheap investment cost despite the availability of renewable energy policies and financial mechanisms (Martin & Rice, 2012). Renewable technologies for RAPS systems also have low dispatch rates (20% - 40%) due to the intermittent nature of renewable sources (ARENA, 2014). These reasons have made it challenging for RETs to penetrate the Australian electricity power supply. However, the need to continuously develop and deploy renewable energy have been intensified by the Mandatory Renewable Energy Target (MRET) and the Paris Agreement. These policies were part of Australia's commitment to increase the share of renewable energy in the electricity mix by 23.5% in 2020 and reduce carbon emissions by 26 to 28% on 2005 levels by 2030 (Australian Government, 2015; Hunt & Macfarlane, 2015). The rapid deployment of RETs can assist in meeting these targets. A framework is then needed by policy makers to create technical options that leads to the provision of environmental friendly electricity supply options at a reasonable cost.

Eco-efficiency, which is defined as the provision of economically viable products or services at the least possible environmental expense, has been used in this present study to link these two pillars of sustainability (Verfaillie & Bidwell, 2000). A framework would be needed to exhibit the environmental and economic valuation of power generating technologies. With a discussion and support from Horizon Power, this MPhil research develops a comprehensive framework to achieve a better eco-efficiency performance of RAPS systems in Western Australia.

1.2 Objectives

The goal of this research is to develop a conceptual framework that can assist in the improvement of the eco-efficiency performance of RAPS systems in Western Australia. This framework uses eco-efficiency theories based on life cycle assessment approaches to determine eco-efficient RAPS options. In order to achieve this goal, the following research objectives have been proposed.

Objective 1: To develop a conceptual model for improving the eco-efficiency performance of RAPS systems in Western Australia

Several sustainable energy frameworks were reviewed from published literature in order to develop a conceptual model for improving the eco-efficiency performance of RAPS systems. Most of the methods and frameworks reviewed have dealt with technical performance, techno-economic assessment (levelized cost of electricity and life cycle costing), and environmental and embodied energy assessment. No conceptual framework so far has been developed for assessing potential eco-efficiency improvements in RAPS systems.

This research develops a comprehensive eco-efficiency analysis (EEA) framework comprising of environmental life cycle assessment (ELCA), life cycle costing (LCC) and eco-efficiency portfolio analysis in selecting appropriate eco-efficiency strategies. This framework has focused on the economic and environmental pillars of sustainability in order to address eco-efficiency requirements of RAPS in Western Australia. The author has recently published this framework in Clean Technology and Environmental Policy as a part of this MPhil thesis (Arceo, Rosano, & Biswas, 2017).
In this study, social life cycle assessment has not been considered. A detailed discussion of this framework to address Objective 1 has been provided in Chapter 3.

Objective 2: To estimate the environmental impacts of the upstream and downstream life cycle stages of the RAPS systems and to identify their environmental hotspots

This research has estimated the impact categories that are relevant in Australia including global warming potential, mineral depletion, fossil fuel depletion, land use and ecological diversity, water depletion, eutrophication, acidification, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical smog, ozone depletion, ionising radiation, human toxicity and respiratory inorganics using ELCA approach. This ELCA has followed ISO 14040-44 (ISO, 2006), which includes goal and scope definition, inventory analysis, impact assessment and interpretation to estimate the environmental impacts. A 'cradle to grave' approach comprising of mining to manufacturing production, construction, operation, maintenance and disposal has been considered as the system boundary. The recycling and remanufacturing of RAPS components were not considered due to lack of information. The functional unit used for estimating energy and material inputs during the life cycle of the RAPS systems for ELCA analysis was the generation of 1 MWh of electricity.

This ELCA has also been used to identify the energy and material inputs that contribute to the largest impacts (hotspots) during the life cycle stages of RAPS. Their causes have been investigated in order to determine appropriate eco-efficiency strategies to further reduce the environmental impacts, as highlighted in Objective 3.

Objective 3: To select appropriate eco-efficiency strategies for the identified hotspots of the RAPS systems to further reduce environmental impacts

According to the World Business Council for Sustainable Development, eco-efficiency involves the efficient utilisation of resources and reduction of wastes for businesses to achieve economic progress (van Berkel, 2007; Verfaillie & Bidwell, 2000). Seven objectives of eco-efficiency strategies including reduction of material intensity, energy intensity and dispersal of toxic substances, improvement of material recyclability, maximised use of renewable resources, extension of product durability and enhancement of service intensity of products or services have been explored to reduce the environmental impacts of the existing RAPS system as discussed in Chapter 4. Follow up ELCAs have been carried out using revised energy and material inputs from the alternative RAPS options to determine environmental improvement potential.

Objective 4: To assess the life cycle costs of the existing and improved RAPS options

A life cycle costing (LCC) approach has been considered to assess economic performance of both existing and environmentally improved RAPS options following Standards Australia/Standards New Zealand (2014). The evaluation of the LCC in Chapter 4 has considered the calculation of the net present values (NPV) in order to determine the cost-effectiveness of various improved RAPS options. The same life cycle inputs, functional unit and system boundary that were used for ELCA have been considered for the LCC in order to maintain the consistency of analysis.

Objective 5: To assess the eco-efficiency performance of both existing and improved RAPS options using eco-efficiency portfolio analysis

The RAPS options are eco-efficient in portfolio analysis when the environmental performance is met in a cost-competitive manner. The results of the ELCA and LCC analyses, as obtained through Objectives 3 and 4 were used for the selection of eco-efficient RAPS options. This has been carried out to synergize the trade-off between environmental impacts and costs. This approach was used as previous studies have found that the integration of environmentally friendly strategies may not always be cost-competitive or vice versa (Arceo et al., 2017; Shonnard, Kicherer, & Saling, 2003).

Sensitivity analysis has been carried out to determine the effect of highly sensitive policy variables, discount rate, diesel price and carbon tax in the eco-efficiency of RAPS options.

1.3 Research Methods

The case study sites considered for EEA analysis were selected in consultation with a local utility provider Horizon Power. Two solar PV-diesel hybrid systems in Marble Bar and Yungngora, Western Australia, and a wind-diesel hybrid system in Coral Bay, Western Australia were considered.

Site-specific information including single line diagrams, power generation equipment specifications, RETs and diesel engine operation, power consumption and future capacity expansion have been sourced from Horizon Power in order to develop a life cycle inventory (LCI) for environmental (ELCA) and economic (LCC) analyses. Other information that were not available from the power distribution utility were gathered from literature and through expert interviews.

HOMER Pro 3.9.1 software was used for estimating the operational inputs of the hybrid systems including electricity generation from diesel engines and renewable energy and diesel consumption. MS Excel 2015 software was used for estimating the material and energy inputs for the mining to material production, construction, maintenance and disposal. These LCIs were then entered into SimaPro 8.2.3 software (PRé-Consultants, 2015) to estimate the environmental impacts for Objective 2.

MS Excel software 2015 was used to estimate the life cycle costs of both existing and improved RAPS options for Objective 4 following Standards Australia/Standards New Zealand (2014). Finally, eco-efficiency portfolio analysis for the selection of eco-efficient RAPS options was carried out using MS Excel software 2015 to attain Objective 5.

1.4 Significance

This research has measured the environmental impacts and costs associated with the electricity generation of RAPS in Western Australia using a life cycle assessment approach. Secondly, this research may assist energy planners and policymakers in the selection of more eco-efficient RAPS options (e.g. optimal operation of diesel engines, maximised renewable energy penetration) using a comprehensive eco-efficiency framework. This research could contribute to the reduction in global environmental impacts such as global warming and fossil fuel depletion whilst generating electricity at a reasonable cost. Finally, this eco-efficiency framework could potentially be considered for application in other Australian states and countries across the globe.

1.5 Thesis Outline

Figure 1.1 shows the outline of this thesis. The six chapters of this thesis are summarised as follows.

Chapter 1 introduces the background, goal, objectives and significance of this thesis.

Chapter 2 presents the review of literature on sustainable energy, renewable energy policies, sustainability assessment tools and eco-efficiency theories for RAPS systems in order to identify the research gaps and formulate research questions.

Chapter 3 presents a conceptual framework for eco-efficiency analysis of RAPS systems. This chapter further discusses the integration of life cycle management tools such as environmental life cycle assessment (ELCA) and life cycle costing (LCC), eco-efficiency strategies and eco-efficiency portfolio analysis to determine eco-efficient RAPS options.

Chapter 4 presents the technical specification and operational characteristics of the hybrid systems in order to develop LCIs for conducting environmental impact assessment, identifying environmental hotspots and selecting eco-efficiency strategies to further reduce environmental impacts. In the second part, economic analysis of existing and improved RAPS options has been carried out using a LCC approach.

Chapter 5 utilises the ELCA and LCC results of Chapter 4 to conduct an eco-efficiency portfolio analysis for selecting eco-efficient RAPS options.

Chapter 6 summarises the final outcomes and discusses how all the research objectives were addressed. Finally, this chapter provides recommendations for future research opportunities.

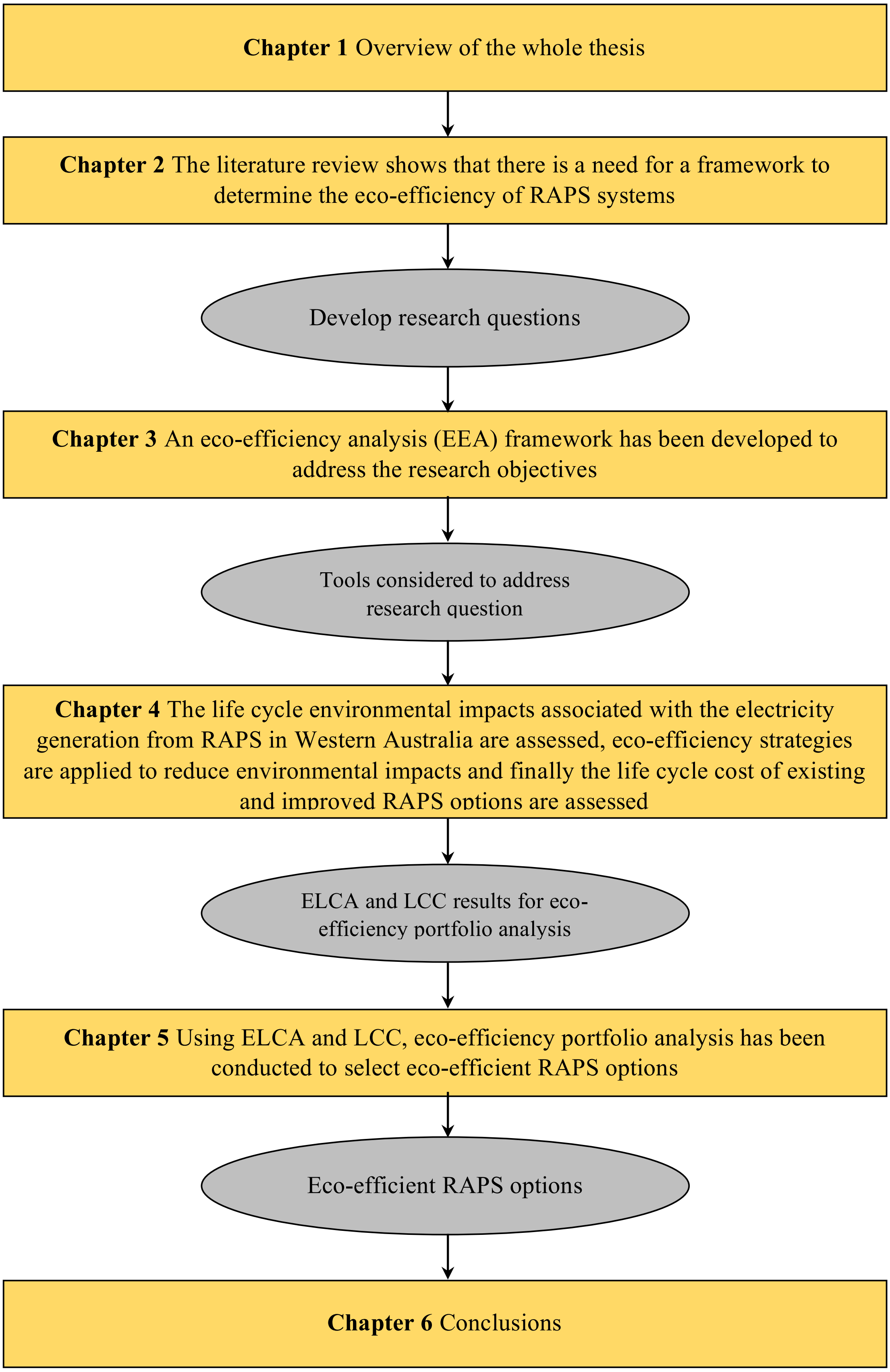


Figure 1.1 Thesis outline

Chapter 2
Literature Review

2.1 Introduction

Energy is an indispensable commodity for the existence and development of the modern society. It drives the economic prosperity of a nation and maintains the well-being of millions of people. However, there is an increasing awareness of how the world's energy system needs to be changed in order to conserve energy for future generations. This chapter aims to review sustainable energy challenges globally, the application of renewable energy technologies (RETs), the barriers to the deployment of renewable energy with particular application to Australia and sustainability tools for sustainable energy assessment.

Present energy systems have been overwhelmingly dependent on fossil fuels to sustain the functional activities of the modern economy. The continuous exploitation of fossil fuels leads to concerns including global resource scarcity, security of supply and health and environmental impacts (Boyle et al., 2003). Although new reserves of oil and gas continue to be discovered due to the advancement in exploration technologies, the depletion of fossil fuels cannot be circumvented. Energy affordability for basic needs will decrease due to a growing scarcity of non-renewable energy sources. Carbon dioxide, nitrogen oxide and sulphur dioxide gases that are emitted from the combustion of these fossil fuels cause global warming, acid rain, photochemical smog and ecotoxicities (Tester et al., 2005). Therefore, the current fossil fuel dependent economy will lead to socially inequitable, economically unsustainable and significant environmental impacts into the future.

The use of sustainable energy provides services to people with minimal detrimental effect on the biosphere and enhances intergenerational equity through the conservation of resources for future generations (Boyle et al., 2003). Three ways to attain sustainable energy scenarios are the 1) implementation of clean technologies that render lower environmental impacts from fossil fuel use, 2) deployment of renewable energy in a bigger scale and 3) improvement of the efficiency of energy distribution and end-use appliances (Golušin, Dodić, & Popov, 2013a; Pardo Martínez, 2015). This research particularly focused on the development and deployment of renewable energy. From a global perspective, the utilisation of renewable energy could assist in the avoidance of environmental degradation and address future energy scarcity (United Nations, 1992).

In Australia, there is a potential to increase the share of renewable energy in the electricity mix of remote area power supply (RAPS) systems, as they are predominantly powered by fossil fuels (ARENA, 2014). Almost half of Australia's RAPS are located in Western Australia's mining towns and agricultural farms. Many power distribution utilities that serve electricity to these RAPS systems still prefer the use of fossil-fuelled generators (Evans & Peck, 2011). The environmental benefits from the use of RETs are hardly given any importance due to the additional costs associated with the integration of these technologies. Energy planning and appropriate policies are required to reduce the environmental impacts of RAPS systems in a cost-effective manner. Therefore, a review of available sustainability tools has been conducted in order to develop a framework to help assess and promote more sustainable energy solutions.

A wide range of available sustainability assessment tools have been reviewed including environmental life cycle assessment (ELCA), life cycle costing (LCC), social life cycle assessment (SLCA), triple bottom line assessment (TBL) and eco-efficiency analysis (EEA). ELCA, LCC and SLCA can evaluate the potential environmental, economic and social implications of RAPS systems. Whilst these three methods can individually assess the three pillars of sustainability, a TBL can provide a framework for consistently integrating environmental, economic and social values (Ozgun, Flanders Cushing, & Buys, 2015). However, TBL is only focused on measuring the performance of a product or system and does not provide opportunities for system improvement. In this regard, EEA has been found to develop strategies to achieve cost-competitive environmentally friendly options (Kicherer, Schaltegger, Tschochohei, & Pozo, 2007; Saling et al., 2002). Although EEA only considers two pillars of sustainability (economic and environmental), this method would be beneficial to address the main concerns of energy planners and policy makers in selecting an environmental friendly RAPS option such as renewables that generates electricity in a cost competitive manner.

This chapter presents the importance of sustainable energy in addressing global resource scarcity and environmental impacts. The discussion includes the barriers that have been experienced by developed countries to deploy renewable energy sources on a much greater scale. Secondly, the progress of RETs in Australia and the barriers to implement these technologies are discussed. Thirdly, the potential of RETs to generate electricity for remote Australian mining and agricultural areas is also discussed. Finally, literature published worldwide within the last 10 years have been reviewed to identify and compare previous and current sustainability assessment tools that can determine the economic, environmental and social implications of RAPS systems. This specifically reviews the aforementioned tools in order to develop a thorough understanding of each method and to determine their potential in developing an eco-efficiency analysis framework for energy assessment.

2.2 Energy and Sustainable Development

Sustainable development is a widely accepted concept for the development of strategies to leave adequate resources for future generations (Golušin et al., 2013a). The well-established definition of sustainable development by the Brundtland Commission has been recently adopted to address global resource scarcity (United Nations, 2007). This concept only encourages human activities that do not have an adverse effect on both the quality of life at present and into the future. Human activities that were considered sustainable need to conform with the economic, environmental and social aspects of sustainable development (Ema, 2015; Golušin et al., 2013a)

A significant application of sustainable development is to secure reliable energy resources for society at a reasonable cost without creating environmental impacts (Kaygusuz & Kaygusuz, 2002). The need for a sustainable energy is crucial due to global fossil fuel diminishing resources and the environmental hazards associated with the consumption of fossil fuels (Boyle et al., 2003). Almost all human activities depend heavily on fossil fuel. If all countries step up their consumption, the current reserves of fossil fuels will be depleted. These resources will eventually be exhausted and alternatives have to be discovered (Tester et al., 2005). Atmospheric pollutants such as carbon dioxide (CO_2), sulphur dioxides (SO_2) and nitrous oxides (NO_x) emitted during the distribution and combustion of fossil fuel are known to be harmful to both environmental and human health (Zahedi, 2010). These anthropogenic GHG emissions are also known to cause climate change, which is increasing the temperature of the earth's atmosphere at an unprecedented rate (Tester et al., 2005).

The fundamental principle of sustainable energy administers the appropriate use of energy at present and evaluates how this affects future energy resources (Golušin, Dodić, & Popov, 2013b). Tester et al. (2005) relates sustainable energy with intergenerational equity since the equitable availability of energy resources is harmonised to the needs of the present and future generations.

Sustainable energy development requires strategies that create progress and stimulate environmental protection, social welfare and economic development (Pardo Martínez, 2015). In order to address these challenges, three energy pathways have been proposed: 1) Conservation of non-renewable resources by introducing 'clean' technologies that substantially reduce emissions from the distribution and consumption of fossil fuels or permanently reducing new reserve exploration, 2) Widespread development and deployment of renewable energy sources, and 3) Improvement of energy efficiency in all phases where energy exists (generation, distribution and consumption). (Boyle et al., 2003; Golušin et al., 2013a; Pardo Martínez, 2015). Strategies for achieving sustainable energy have been implemented in many developed countries including European and Scandinavian countries, Japan, USA and Canada (Golušin et al., 2013a).

The familiar connection between sustainable energy and renewable energy have made the second strategic priority of sustainable energy an effective solution (Kaygusuz & Kaygusuz, 2002). The development and deployment of renewable energy treats existing sustainable energy concerns since its source of energy can be replenished by physical processes which are renewable and associated environmental impacts are generally lower than fossil fuel technologies (Boyle et al., 2003). The United Nations convention on climate change in 1992 has encouraged the widespread use of renewable energy (United Nations, 1992). Its promotion was heightened by the Kyoto Protocol in 1997, which identified renewable energy as a vital strategy to reduce GHG emissions (United Nations, 1998).

An effective policy framework is a highly compelling factor in the development and deployment of renewable energy. Every country's government have played a critical role in developing policies and regulatory frameworks to create opportunities for investment in order to accelerate renewable energy deployment (IRENA & GWEC, 2012). The current position of Germany in the utilisation of renewable energy can be attributed to years of progressive legislation (Grosskopf & Meisen). The country's renewable energy policies were introduced in 1970s when electricity generation from nuclear power plants was slowly reduced. These efforts were further supported by international climate change and energy policies (IRENA, 2015).

Currently, Germany receives more than 50% of its electricity supply from solar and wind power. A Feed-in-Tariff (FiT), which was intensified by the German Renewable Energy Sources Law of 2000 has increased the national installed renewable energy capacities (IRENA, 2015; IRENA & GWEC, 2012; Mormann, Reicher, & Hanna, 2015). This FiT rate was intended to reduce the price of solar and wind power technologies by providing investors with a solid return of around 8% (Harvey, 2013). The willingness of the German government to pay for the investments was to ascertain that there would be sufficient cheap and clean energy available into the future. Other significant renewable energy policies in Germany include incentives for large renewable energy generators to sell their electricity in the market instead of selling it under the FiT and a dynamic FiT rate that automatically adjusts upward or downward according to deployment success of renewable energy (Mormann et al., 2015). All of these policies have helped Germany to attain its renewable energy targets ahead of schedule (12.5% set in 2004 was achieved in 2007, 20% in 2020 was reached in 2011) (IRENA, 2015; Mormann et al., 2015). In addition, these policies have diversified the energy mix of Germany, liberalised the electricity market structure, lessened dependence on electricity imports and created a large renewable energy workforce (IRENA, 2015).

Similar to Germany, the deployment of renewable energy in Denmark was driven by legislation to replace fossil fuels with renewable energy (Greenpeace, 2014). Denmark is a pioneer in the provision of subsidies for the deployment of wind power technologies through the FiT system and is also has the first nation to introduce environmental taxation to encourage the switch to clean technologies (IRENA & GWEC, 2012). Electricity cooperatives that involve the local distribution and transmission utilities also contributed a significant role in the public acceptance of wind power technologies (IRENA & GWEC, 2012). Despite the Danish stagnation in the deployment of renewable energy from 2001 to 2008 due to a change in government and the phase-out of the FiT system, the renewable energy market recovered after the United Nations Climate Change Conference in 2009. New policy guidelines created initiatives for Denmark to have a transition into renewable energy by increasing competition in the energy sector and encouraging investment on renewable energy plants (Danish Government, 2011).

The review of these two developed countries has shown that the selection of policy frameworks is distinct for each country, suggesting that support mechanisms are not similar for all countries. The success of renewable energy deployment in Germany and Denmark is not solely attributed to the policies created by the respective governments but also to public response. In the case of Australia, the potential for vast deployment of renewable energy is significant but uptake to date has been limited.

2.3 Renewable Energy Situation in Australia

In Australia, the need for the development and deployment of RETs is significant not only to address the security of energy supply but also to address the growing concerns of climate change (United Nations, 1992; Yates & Greet, 2014). The electricity generation sector in Australia accounts for 35% of the total GHG emissions (Department of Environment, 2016). The predominant use of coal and gas for electricity generation contributed to the large share of the national GHG inventory. This section presents the existing structure of electricity network in Australia, policies and regulatory frameworks related to renewable energy and the challenges experienced by the Australian renewable energy industry.

The electricity network in Australia generates electricity from centralised fossil-fuelled generators from which electricity is transmitted through high voltage transmission networks, then transported to distribution networks and then supplied to customers (AER, 2017). The widespread dependence on fossil fuels for electricity generation is attributed to abundant and relatively cheap coal and gas resources (Stewart, 2017). The National Electricity Market (NEM) operates the electricity grid that accounts for more than 90% of demand requirement in Queensland, New South Wales, the Australian Capital Territory, Victoria, Tasmania and South Australia (AEMO, 2010). The rest of the demand is serviced by the South West Interconnected System (SWIS) and North West Interconnected System (NWIS) in Western Australia and by the Darwin Katherine Interconnected System (DKIS) in the Northern Territory (AER, 2007). These electricity networks provide electricity to major cities across Australia except in the remote and regional communities.

Figure 2.1 shows the electricity mix in Australia between 1990 and 2015, which shifts from the use of coal to natural gas. Early policy and regulatory mechanisms that were designed to assist in the uptake of renewable energy including the carbon pricing, Feed-in-Tariff (FiT) and the Mandatory Renewable Energy target (MRET) have not made renewable energy a substantial contributor to total electricity generation. Unless the focus will have a transition from reliance on clean technologies (e.g. natural gas plants) to utilisation of RETs, electricity generation can potentially have a large influence on climate change mitigation. The exploitation of renewable resources is restricted due to the high cost of RETs compared to non-renewable technologies, uncertainties in energy policies and the lack of institutional acceptance (Byrnes, Brown, Foster, & Wagner, 2013).

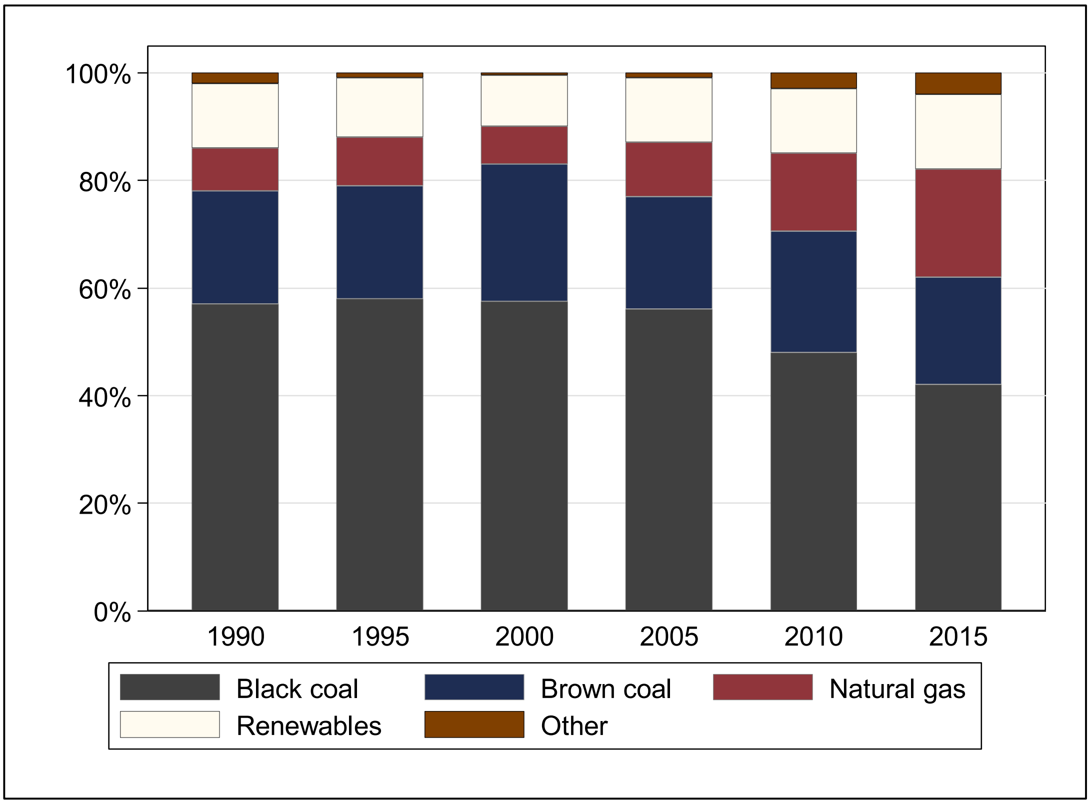


Figure 2.1 Australian electricity generation mix (Office of the Chief Economist, 2016)

The cost of electricity generated from fossil fuels is generally lower than RETs due to the unaccounted external costs (e.g. environmental costs) (Koomey & Krause, 1997; Markandya, 2012; Timmons, Harris, & Roach, 2014). The cost of electricity generated from RETs would have been lower if environmental and societal costs have been incorporated. The uncertainties associated with regulatory and policy frameworks has also become a barrier to the deployment of renewable energy (Byrnes & Brown, 2013; Byrnes et al., 2013). In Queensland, renewable energy participants relying on financial support from the government are vulnerable to the risk of changes in policies due to the lack of administrative and legislative support structures (Martin & Rice, 2012). This led to a low development of medium to large scale renewable energy, as the incentives provided to renewable power providers and customers were insignificant (ARENA, 2014; DOE, 2006).

The Bureau of Resources and Energy Economics (BREE) suggests that a potential 20% electricity generation from renewable energy can be achieved through appropriate policy mechanisms (BREE, 2014). Recently, the Australian Renewable Energy Agency (ARENA) was established by the Australian Government to assist in the deployment of RETs through research and development, industry development, commercialisation and information dissemination (ARENA, 2014). ARENA highlighted the large potential of renewable energy in remote areas that are mostly powered by fossil fuels. In Queensland, various resources including solar, wind and geothermal has been utilised for the remotes areas in the central and northern region (ARENA, 2014). Similar to the integration of grid-connected renewable energy, government support will also be needed to facilitate the transition from diesel power generation to renewable energy in RAPS. A review on remote area power supply (RAPS) and renewable energy has been discussed in the next section to further emphasise the potential of RETs in Australia.

2.4 Sustainability Aspect of Remote Area Power Supply in Australia

RAPS in Australia contributes to 7% of the total electricity generation for only 2% of the population. In 2012, RAPS systems generated 15,575 GWh of electricity (ARENA, 2014). This supplies electricity to remote areas including agricultural farms, mine facilities, remote communities and infrastructure wherein majority of the electricity is delivered to remote mining industries (Evans & Peck, 2011). The distribution of existing RAPS networks in Australia is mostly concentrated in Queensland, South Australia, Western Australia, Northern Territory and Tasmania (Figure 2.2). In 2012, Western Australia contributed the largest share of electricity generation (8,880 GWh, 56.16%) followed by Queensland (3,339 GWh, 21.50%), Northern Territory (3,274 GWh, 20.71%), South Australia (236 GWh, 1.49%) and Tasmania (23 GWh, 0.15%) (ARENA, 2014).

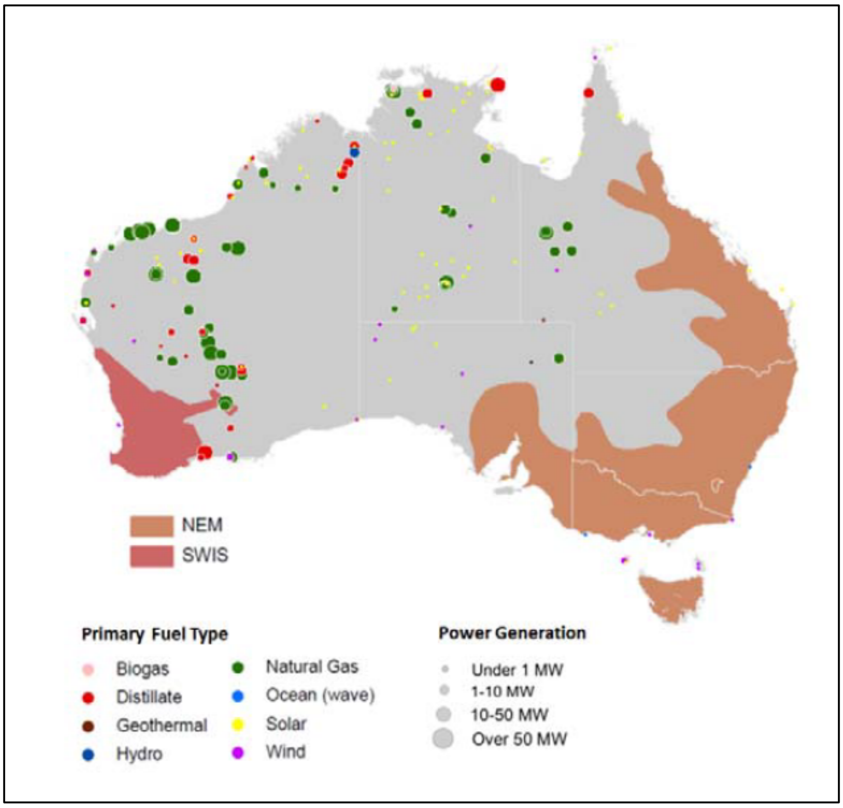


Figure 2.2 Existing RAPS systems in Australia (ARENA, 2014)

Electricity generated from RAPS in Australia is mostly sourced from natural gas and liquid fuels (e.g. diesel) (Figure 2.3). Only a small portion of electricity is generated from renewables. These RAPS systems are operated by government and privately owned power distribution utilities including Ergon Energy in Queensland, Power and Water Corporation in Northern Territory, and Horizon Power and Synergy in Western Australia. At a state and territory level, electricity demand was increased by 8% in Western Australia and by 5% in the Northern Territory due to the expansion in RAPS for mining exploration activities (Office of the Chief Economist, 2015a). The mining industry in Australia is currently receiving pressure to reduce environmental emissions from mining activities. In Western Australia, an impending 3,617 GWh of electricity demand due to the rapid expansion of remote mining projects can potentially increase GHG emissions by 2.21 Mt CO_2 annually (ARENA, 2014; Department of Mines and Petroleum, 2015). Renewable energy has been identified as an effective way to ensure energy security for RAPS with reduced environmental impact.

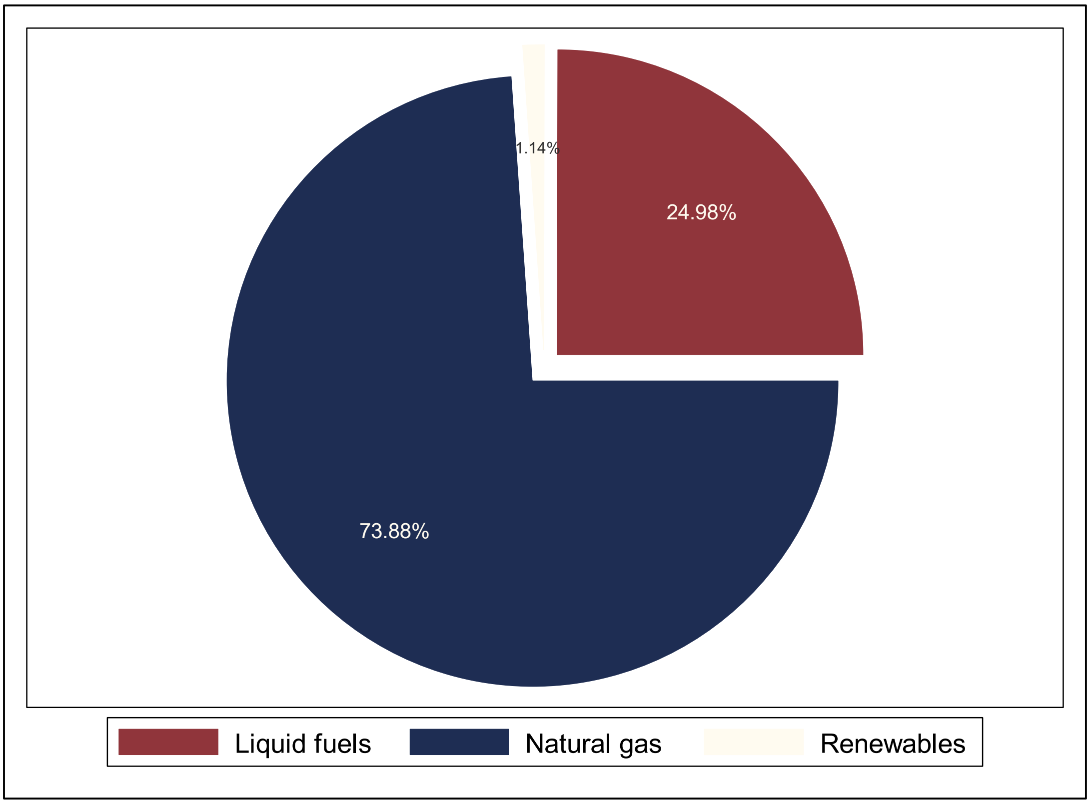


Figure 2.3 Electricity generation by fuel type for RAPS in Australia (ARENA, 2014)

Western Australia has vast sources of renewable energy including the highest solar radiance in the Pilbarra and Mid-West regions and strong wind resources in South West and Great Southern regions (Office of the Chief Economist, 2015b). ARENA (2014) suggested that RAPS can benefit from reducing emissions and offsetting fuel expenses. However, previous researchers have investigated the high capital and recurring maintenance costs of RET integration for RAPS in Western Australia, which has slowed down the deployment of renewable energy (Jennings & Healey, 2001; Lowe & Lloyd, 2001; McHenry, 2009). Energy planners have also expressed reliability concerns with RET integration as significant levels of renewable energy in a distribution system can cause voltage and frequency fluctuations (Anees, 2012; ARENA, 2014; Evans & Peck, 2011; Karimi, Mokhlis, Naidu, Uddin, & Bakar, 2016). In addition, energy planners have been concerned with the use of RETs as operational and logistical experience and confidence in conventional technologies is well understood (ARENA, 2014; Evans & Peck, 2011). Hybridising fossil fuel and renewable technologies to form an integrated RAPS system could address some of these technical and economic challenges (Holtmeyer, Wang, & Axelbaum, 2013; Jamal, Shafiullah, Carter, & Urmee, 2017).

A fossil fuel-renewable hybrid system has been found to prevent voltage and frequency fluctuations (Evans & Peck, 2011). The price of renewable integration into a fossil-fuelled RAPS system increases at higher capacity but the large capital cost can be compensated by the fuel cost savings (Arceo et al., 2017; Evans & Peck, 2011). For instance, the solar PV-diesel hybrid system in Nullagine, Western Australia has 30% annual solar energy penetration which saves 400,000 litres of diesel every year. In order to accelerate renewable energy development through hybrid systems, energy planning is essential to identify ways of generating environmentally friendly electricity in remote areas at a reasonable cost. Sustainability assessment tools can help achieve this objective.

A review of available sustainability assessment tools is discussed in the next section to help develop a framework for accelerating the penetration of RETs in Western Australia.

2.5 Review of Sustainability Assessment Tools for Power Generation Technologies

Several studies suggested the use of sustainability assessment tools and frameworks by the energy sector for assessing economic, environmental and social implications in the selection of power generating technologies and for decision making purposes (Allan, Eromenko, Gilmartin, Kockar, & McGregor, 2015; Holtmeyer et al., 2013; Petrillo et al., 2016; Schofield, 2011; Smith et al., 2015; Väisänen et al., 2016). This section provides a review of sustainability assessment tools for different power generation technologies. Various research databases including Elsevier Science Direct, Springerlink and ProQuest were used to search for keywords that include “power generating technology”, “renewable energy”, “solar PV/photovoltaic”, “wind generator”, “life cycle assessment”, “life cycle costing”, “social life cycle assessment”, “triple bottom line” and “eco-efficiency”. The peer reviewed journals selected were those published over the last 10 years and have demonstrated an analysis on the economic, environmental or social implications of power generating technologies.

The significance of various tools such as environmental life cycle assessment (ELCA), life cycle costing (LCC), social life cycle assessment (SLCA), triple bottom line (TBL) and eco-efficiency analysis (EEA) for sustainability assessment of power generating technologies were discussed in the following sections.

2.5.1 Environmental life cycle assessment

ELCA is an effective tool that assists in determining the environmental impacts of a product or service system throughout its life cycle. This is also widely used in implementing environmental improvement opportunities and to compare existing systems with the improved scenario (ISO, 2006). The four interconnected procedures in performing ELCA is shown in Figure 2.4.

1. *Goal and scope definition*. This initial stage sets the boundaries and limitations of the analysis and outlines the aims and methods to meet the goals (Schofield, 2011).
2. *Inventory analysis.* This establishes the basis for computational analysis of the study by quantifying all the associated material and energy inputs and emissions of the product or service system (Bekkelund, 2013).
3. *Impact assessment.* This aims to estimate the magnitude and evaluate the importance of the potential environmental impacts (Bekkelund, 2013; Fu, Liu, & Yuan, 2015; Schofield, 2011).
4. *Interpretation.* This highlights the main findings and determines how each process and their emissions contribute to the environmental impacts (Schofield, 2011). Further strategies can be implemented to reduce these investigated impacts (Bekkelund, 2013).

ELCA uses a functional unit as a reference for calculating the associated inputs and output of a product or service system (Heijungs & Guinée, 2012). A functional unit for assessing the environmental impacts of power generation systems could be the generation of 1 kWh or 1 MWh of electricity (Spath, Mann, & Kerr, 1999). The system boundary for ELCA determines the processes included in the overall analysis to define the temporal, spatial and production chain limits (Fuels From Waste, 2013). A cradle-to-grave analysis is the most widely used system boundary for ELCA, which includes all the main life cycle stages of a product or service system such as extraction and production of raw materials, use and eventual disposal (Klopffer, 2014).

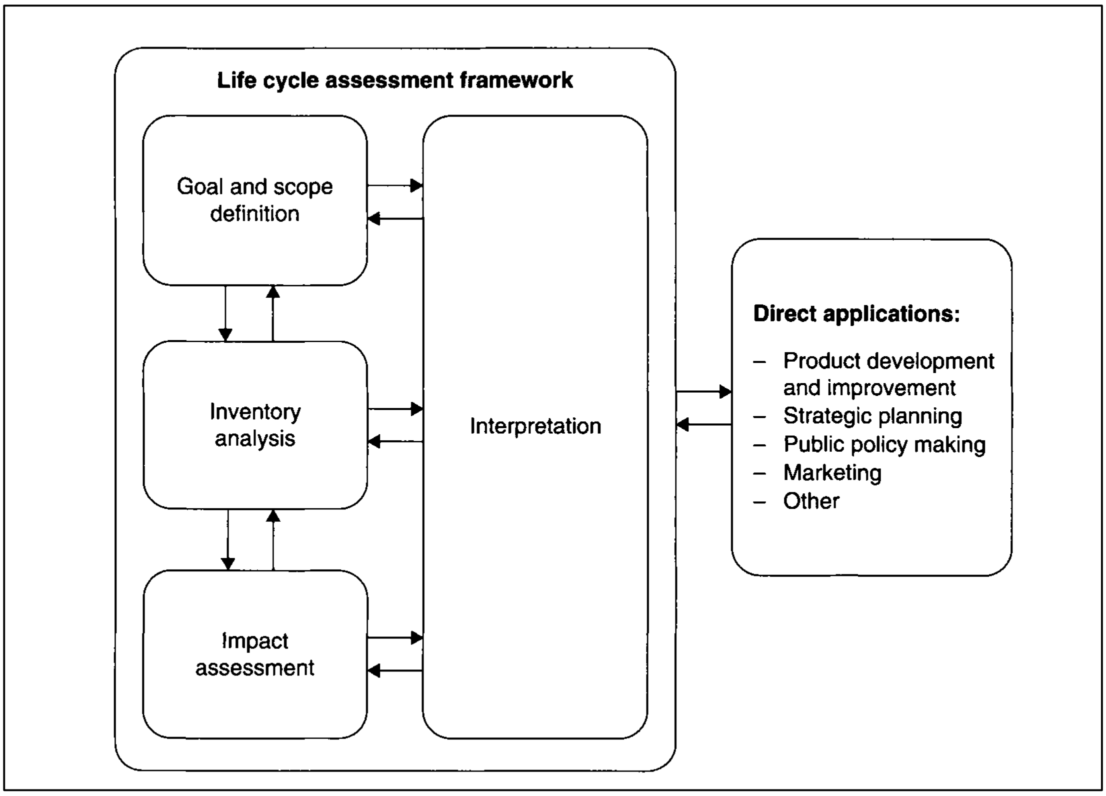


Figure 2.4 Methodological framework for life cycle assessment (ISO, 2006)

ELCA methodological choices have to be made in order to draw out conclusions from the analysis. Attributional life cycle assessment (ALCA) and consequential life cycle assessment (CLCA) are the two main approaches for generating environmental assessment outcomes (Buyle, Braetb, & Audenaerta, 2014). The choice of the approach depends on the defined goal and scope of the study. ALCA describes the environmental burdens on the physical flows to and from the system over its life cycle, whereas CLCA considers further investigation on the environmental flows in response to potential decisions (Kua & Kamath, 2014; Swiss Centre for Life Cycle Inventories, 2012). In addition, ALCA provides relevant and significant information in formulating various alternatives that deliver changes while CLCA concentrates on the outcome of decisions (Tillman, 2000; Yang, 2016). This research considered ALCA since the goal is to find the largest contributor to environmental impacts (hotspots) in the existing RAPS systems in order to implement potential environmental improvement strategies.

A review of available ELCA studies on power generating technologies such as solar photovoltaics (PV), wind generators and hybrid energy systems is now discussed.

2.5.1.1 Review of environmental life cycle assessment (ELCA) of solar PV

The application of ELCA for assessing the environmental performance of solar PV technology over the last 10 years was summarised in Table 2.1. The review considered ELCAs conducted in developed and developing countries. Most of the ELCAs were performed in China mainly because it is the largest solar PV manufacturer in the world and their need to meet environmental obligations is quite high (Puttaswamy & Ali, 2015). The lessons and information acquired from the review of solar PV ELCAs were summarised and considered for the current study.

Most of these ELCAs estimated a number of environmental impacts to encompass the extent of human, environment and resource damage from generating electricity from solar PV. The ELCA conducted by Chen, Hong, Yuan, and Liu (2016) included sixteen mid-point impact categories consisting of climate change, terrestrial acidification, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, metal depletion, freshwater ecotoxicity, ozone depletion, marine ecotoxicity, ionising radiation, agricultural land occupation, natural land transformation, urban land occupation, water depletion and fossil depletion. ELCAs conducted by Fthenakis and Kim (2011), Fu et al. (2015) and Menoufi, Chemisana, and Rosell (2013) also considered estimating various impact categories to determine the detrimental effects on ecosystems, natural resources and human health. The energy payback time (EPBT) of solar PV was also assessed by some studies (Kannan, Leong, Osman, Ho, & Tso, 2006; Sharma & Tiwari, 2013). In Australia, the study of grid-connected solar PV in Queensland evaluated the EPBT and various environmental impacts (Yu & Halog, 2015).

The life cycle inventories (LCIs) of these ELCAs were assessed based on a defined functional unit. All studies reviewed used a functional unit of 1 kWh or 1 MWh of electricity generated. The system boundary considered by these ELCA studies were either material extraction to transportation (cradle to gate) or material extraction to disposal (cradle to grave). Bekkelund (2013) included only the extraction of materials and manufacturing of the modules. while Zhong, Song, and Loh (2011) modelled and evaluated different end-of-life disposal methods including landfill, recycling and incineration. Majority of these studies not only considered solar PV but also the balance of system (BOS) (Menoufi et al., 2013; Wu, Ma, Ji, & Ma, 2017; Yu & Halog, 2015). The

BOS encompasses all components of a PV system other than the panels and may include cables, wires, inverters, batteries, frames and supporting structures

ELCAs have been widely used to identify environmental hotspots. These ELCA studies show that the solar PV module production stage is responsible for 60% to 90% of the primary energy consumption and GHG emissions regardless of the solar cell technology (Hou et al., 2016; Kannan et al., 2006; Menoufi et al., 2013; Stoppato, 2008; Sumper, Robledo-García, Villafáfila-Robles, Bergas-Jané, & Andrés-Peiró, 2011; Tsang, Sonnemann, & Bassani, 2016; Yu & Halog, 2015). This is mainly attributed to large electricity and fuel consumption during the module production (Fthenakis & Kim, 2011; Fu et al., 2015; H. Kim, Cha, Fthenakis, Sinha, & Hur, 2014; Wu et al., 2017) followed by the extraction and production of energy intensive raw materials such as silver paste, aluminium and solar glass (Bekkelund, 2013; Chen et al., 2016). The life span of a solar PV system, which commonly ranges from 20 to 30 years was found to not affect the overall environmental impacts due to the negligible influence of the use and maintenance stages (Chen et al., 2016; Zhong et al., 2011).

Potential improvement strategies were implemented by some studies to mitigate the environmental impact intensive solar PV production stage. Zhong et al. (2011) suggested that recycling of solar PV materials has environmental credits, but the benefit currently received from this disposal scenario is not yet fully maximised. Kannan et al. (2006) suggested that improving the solar PV module production can potentially reduce environmental impacts by 41%, while changing the support structure from aluminium to concrete can reduce these impacts by 18%.

In the review of contemporary solar PV ELCAs, variations in the impact assessment results was observed (Baharwani et al., 2014; Peng, Lu, & Yang, 2013; Sherwani, Usmani, & Varun, 2010). The reason for this is the lack of specific guidelines used in the selection of system boundaries and the differences in the solar PV technology, solar radiation, installation method, system size and BOS components assessed. A guideline for conducting solar PV ELCA in the RAPS system of Western Australia is proposed in the next chapter in order to assist with potential benchmarking.

Table 2.1 Summary of contemporary solar PV ELCAs reviewed

Solar PV LCA Literature	Aims and Objectives	Results
Baharwani et al. (2014)	– The study reviewed previous ELCA studies of solar PV technologies including mono-crystalline, poly-crystalline, amorphous thin-film systems.	– The study found that silicon panels have better energy conversion efficiency but consume more energy for manufacturing than thin-film solar panels. Silicon panels also have higher GHG emissions. – The difference in GHG emissions and energy consumption is also caused by the variability in the performance of the solar PV systems (incoming solar radiation, BOS components, life expectancy and conversion efficiency).
Bekkelund (2013)	– The goal was to assess the environmental impacts of a rooftop, grid-connected solar PV system. This study compared four solar cell types including multi-Si (Elkem solar and Siemens method), CdTe and CIGS. – The functional unit was the generation of 1 kWh of electricity supplied to the grid. – The system boundary only included the mining to material production and manufacturing of the solar PV panels.	– For silicon panels, the production of silicon was the largest contributor in most environmental impacts followed by the production of aluminium, production of solar glass and manufacturing of multi-Si modules. – For thin-film panels, the manufacturing of thin-film modules was the largest contributor to all environmental impacts due to the use of glass and aluminium.
Chen et al. (2016)	– The aim was to evaluate the environmental impacts of mono-Si panels and identify approaches for potential environmental improvement. – The functional unit was the production of 1 kWp of a mono-Si module. The present study assumed a 25-year lifetime for the solar cells. – The system boundary only covered the production stage.	– The results of the normalised environmental impacts show that human toxicity, marine ecotoxicity and metal depletion have the most contribution to the overall environmental impact followed by climate change, fossil depletion, particulate matter formation and terrestrial acidification.

Solar PV LCA Literature	Aims and Objectives	Results
		– The processes that contributed the most environmental impacts were electricity production, silver paste production and mono-Si wafer production.
Fthenakis and Kim (2011)	– The goal was to review previous ELCAs of three silicon and one thin-film solar PV technologies. The metrics for analysis included the calculation of EPBT and estimation of GHG emissions. – The system boundary included the mining of raw materials, their processing and purification, manufacturing of the modules and BOS components, installation, operation of the system, decommissioning and disposal stages.	– The use of electricity and fuel during the material and module production stages were the main sources of GHG emissions and energy consumption. These energy intensive processes also attributed the most to the EPBT of solar PV technologies.
Fu et al. (2015)	– The goal was to assess the life cycle environmental impacts of solar PV systems in China and provide a basis for policies on the sustainable development of the industry. – The functional unit of the ELCA was the generation of 1 kWh of electricity on a 200 W_p multi-Si PV panel. The lifespan of the PV system was 25 years. – The system boundary included silica extraction, silicon bar and ingot growth, cell and module fabrication, aluminium frame production. BOS was not considered due to its small influence on the environmental impacts.	– The primary energy demand, carbon dioxide, phosphate, sulphur dioxide and dichlorobenzene emissions were mainly due to electricity consumed during the production stages. The emissions were high as Chinese electricity was mainly generated from coal-fired power plants. – The results of the normalised environmental impacts show that acidification was the largest contributor to the overall environmental impact (40.6%) followed by global warming potential (27.5%), photochemical oxidation creation potential (15.3%) and human toxicity (10.4%).
Hou et al. (2016)	– The goal of the study was to investigate the environmental impacts of grid-connected solar PVs from crystalline silicon modules. The GHG emissions and energy consumption during each life cycle stage were estimated.	– More than 84% of the total GHG emissions and total energy consumption occurred during the manufacturing of the solar PV panels. – The production of solar grade silicon was the most GHG and energy intensive process.

Solar PV LCA Literature	Aims and Objectives	Results
	– The system boundary included quartz mining, solar grade silicon purification, silicon ingot growth, wafer slicing, solar cell and module production. This also covered the solar PV system integration, construction, operation and end-of-life-disposal stages	
Kannan et al. (2006)	– The goal was to quantify the primary energy use and GHG emissions of the generation of 1 kWh of electricity by a solar PV system. – The system boundary included the material extraction and manufacturing of the solar panels, inverters and supporting structures, installation, operation and decommissioning stages.	– The EPBT of the solar PV system was estimated to be 27% of the modules' expected life time of 25 years. – The GHG emissions of the entire system mainly occurred from the energy used in the manufacturing of the solar PV panels and BOS. – Implementation of improvement strategies (e.g. technology improvement, change of support structure and solar PV efficiency improvement) reduce both the primary energy use and GHG emissions.
H. Kim et al. (2014)	– The goal was to examine the environmental performance of a CdTe solar PV system in terms of global warming potential and fossil fuel consumption. The solar PV system consists of the solar PV panels and BOS. – The functional unit was the generation of 1 kWh of electricity from a 100 kW_p solar PV system for a lifetime of 30 years. – The system boundary covered material extraction, manufacturing of cadmium telluride solar PV, installed and use stages. This study excluded the recycling and disposal stages.	– The electricity used in the production of panels was the main contributor to global warming potential (27.3%) and fossil fuel consumption (45.2%). This is attributed to the energy mix of Malaysia, which mainly generates its electricity from coal and natural gas.

Solar PV LCA Literature	Aims and Objectives	Results
Menoufi et al. (2013)	– The aim was to examine the environmental performance of a building integrated concentrated photovoltaic system. – The system boundary emphasized on the assembly stage and considered the impact of the whole installation.	– The normalised results show that the dominant environmental impacts were fossil fuel depletion (61.6%), respiratory inorganics (17%) and climate change (9.1%). – The panel manufacturing and building remodeling contributed the largest to all environmental impacts.
Peng et al. (2013)	– The study reviewed ELCAs of five types of solar PV systems including mono-Si, multi-Si, a-Si, CdTe thin-film and CIGS thin-film.	– The mono-Si PV technologies have the highest life cycle energy requirement followed by thin-film solar PV technologies. – The energy requirement for each solar PV technology varies due to the differences in manufacturing processes, installation methods, location and weather conditions.
Sharma and Tiwari (2013)	– The goal was to determine the EPBT of a stand-alone PV system with a useful life of 30 years.	– The calculated EPBT of the studied stand-alone PV system was 18.37 years for rooftop mounting and 18.93 years for ground mounting. The potential maximum energy output performance conditions of the systems can improve the EPBT by 31.6% to 35.55%.
Sherwani et al. (2010)	– The study reviewed previous ELCA studies of solar PV technologies including a-Si (5 studies) mono-Si (7 studies) and multi-Si (7 studies).	– EPBT and GHG emissions were the most common indicators assessed for solar PV technologies. – Thin film solar PV modules release less GHG emissions and consume less primary energy, but its efficiency is lower than silicon modules. – The variation in the EPBT and GHG emissions were dependent on the type of solar cell, solar radiation, installation methods, size of the system, BOS components and lifetime of the system.

Solar PV LCA Literature	Aims and Objectives	Results
Stoppato (2008)	– The goal of the LCA was to evaluate the gross energy requirement and global warming potential of solar PV manufacturing process. – The functional unit was defined as the production of a 0.65 m^2 multi-Si panel. – The system boundary covered silica extraction until final panel assembling.	– The life cycle stages that contributed the most in both the gross energy requirement and global warming potential were the transformation of metallic silicon into solar silicon (47.27%, 47,61%) and panel assembly (18.26%, 18.39%).
Sumper et al. (2011)	– The aim was to assess the EPBT and GHG emissions of a 200 kW_p multi-Si rooftop PV panel. – The functional unit was assessed based on the generation of 1 kWh of electricity. – The system boundary covered the manufacturing of photovoltaic modules, inverters and support structures, installation, transport, use and maintenance stages.	– The production of solar PV panels emits the highest GHG emissions and consumes the largest energy among other life cycle stages. – The EPBT of the current system is 80% lower than its expected life time of 20 years.
Tsang et al. (2016)	– The goal was to compare the life cycle environmental impacts of a polymer based organic PV technology with silicon technology. – The functional unit was the life cycle generation of electricity in kWh of a solar rooftop array over 25 years. – The system boundary included the impacts from raw material extraction, processing, panel manufacturing, use and end-of-life disposal stages.	– The organic PV panels have lower environmental impacts than silicon panels. – The manufacturing of BOS attributed the largest environmental impacts for organic PV panels, while the production of solar cells contributed the largest impacts for silicon PV panels.
Wu et al. (2017)	– The aim was to assess the total life cycle energy of a 1 MW on-grid ground-mounted solar PV in China. The operational period of the solar PV system was 30 years. – The system boundary included only the material extraction and manufacturing of multi-Si module and	– The EPBT of the system was 2.3 years. This result was likely overestimated as transportation and operational energy inputs were not included in the analysis. – The electricity used for manufacturing the wafers, solar cells and panels contributed the most in the overall life cycle energy of the system.

Solar PV LCA Literature	Aims and Objectives	Results
	the BOS (inverter, cables, controller, junction boxes and battery).	
Yu and Halog (2015)	– The goal was to find the principal problem in the environmental performance of solar PV projects in Australia. – The functional unit was defined as the generation of 1 kWh of electricity by the University of Queensland solar PV panels. The solar PV system has an operational lifetime of 30 years. – The system boundary included the acquisition of raw materials, their processing, module manufacturing, installation, use, maintenance and disposal.	– The solar PV module production has the largest contribution to all evaluated environmental impacts.
Zhong et al. (2011)	– The goal was to model the end-of-life disposal methods and to assess the life cycle environmental impacts of a mono-Si solar PV panel. – The system boundary covered the material extraction and manufacturing of the PV panels, installation and disposal stages.	– The results of the normalised environmental impacts show that the fossil fuel use has the highest environmental influence followed by respiratory inorganics and acidification. – The process to manufacture silicon wafers and the fabrication of the PV cells contributed the largest to climate change, fossil fuel use, respiratory inorganics and acidification. – The increase in carcinogens, ecotoxicity and mineral use were attributed to the use of toxic chemicals, lead, cadmium, copper and silicon. – The disposal stage contributed to the life cycle impacts. The small quantity of waste recycled from PV modules shows that recycling benefits is not fully maximised.

2.5.1.2 *Review of environmental life cycle assessment (ELCA) of wind generators*

The review of ELCA studies of wind generator technologies conducted over the last 10 years is summarised in Table 2.2. The individual case studies on the environmental burdens and potential policy options for wind generators in both developed and developing countries is reviewed. In Australia, no ELCA study has been conducted to date despite the continuous increase in wind power plant generation. The lessons and information acquired from the review of international wind generator ELCAs was considered in this current study.

The impact assessment of wind generators varied due to differences in ELCA objectives. Some estimated life cycle global warming potential and primary energy consumption only while some estimated multiple environmental impacts. Ardente, Beccali, Cellura, and Lo Brano (2008), Uddin and Kumar (2014) and Kabir, Rooke, Dassanayake, and Fleck (2012) estimated acidification, eutrophication and ozone depletion impacts, while Demir and Taşkın (2013) and Xu, Pang, Zhang, Poganietz, and Marathe (2017) estimated all possible environmental impact categories including abiotic depletion, human toxicity, photochemical oxidation and ecotoxicities. Tremeac and Meunier (2009) and Rashedi, Sridhar, and Tseng (2013) estimated damage categories in terms of human health, natural environment and resources.

The LCIs of these ELCAs were calculated based on their functional units and the majority of these studies used per kWh or MWh of wind electricity generation (Al-Behadili & El-Osta, 2015; Ardente et al., 2008; Demir & Taşkın, 2013; Garrett & Rønde, 2013; Oebels & Pacca, 2013; Tremeac & Meunier, 2009). Few studies based their functional unit on temporal aspects such as Glassbrook et al. (2014) and Guezuraga, Zauner, and Pölz (2012) who calculated their LCIs in annual electricity generation potential. The operational period considered in wind electricity generation by most of these studies was 20 years (Kabir et al., 2012; Oebels & Pacca, 2013; Tremeac & Meunier, 2009).

Most studies have considered a cradle-to-grave system boundary to include the life cycle environmental implications of wind electricity generation. This encompasses the extraction of raw materials for the production of wind generator components, their transportation to wind farm site, operation and maintenance, and eventual disposal. Oebels and Pacca (2013) excluded the dismantling and disposal stages due to lack of available information on wind generator end-of-life pathways. The transmission system components were not included in the current study, as Y. Wang and Sun (2012) indicated that these only constitute less than 1% of the overall impacts.

A hotspot analysis has been conducted by these ELCAs to identify stages of greatest impact for implementation of potential improvement opportunities. The ELCAs have found that the production of wind generator components constituted more than 50% of all environmental impacts (Ardente et al., 2008; Kabir et al., 2012; Oebels & Pacca, 2013). The large quantity of steel that was used to manufacture the tower contributed the largest share of impacts (25 to 30%) followed by nacelle (15%) and foundation (10 to 15%) (Garrett & Rønde, 2013; Guezuraga et al., 2012). Whilst the energy and emission intensity of producing steel is not as high as copper, its large mass composition (>48%) made it the environmental hotspot (Rashedi et al., 2013; W. C. Wang & Teah, 2017). The environmental impacts of the transportation of wind generator components were considerably high due to the long distance transportation of heavy components from different parts of the world. The operational stage of the wind generators was found to contribute the least environmental impact (Al-Behadili & El-Osta, 2015; Uddin & Kumar, 2014).

Most of the wind generator ELCAs have suggested the replacement of the materials used for producing the wind generators with environmentally friendly materials, which could reduce associated environmental impacts. Rashedi et al. (2013) recommended replacing steel in the nacelle with aluminium alloy due to its lower emission intensive production. The replacement of generator blade material with fiberglass can also reduce primary energy consumption by 40% and global warming potential by 22% (Uddin & Kumar, 2014). Oebels and Pacca (2013) observed a 6.4% reduction in emissions with the replacement of a steel tower by a concrete tower. An increase in recycling rates is another strategy that can reduce impacts due to environmental credits received from the recovery of materials. Guezuraga et al. (2012) determined that a reduction of 43% in primary energy consumption and 44% in global warming potential can be attained by wind generator recycling.

A guideline for conducting wind generator ELCA in a RAPS system for Western Australia is proposed in the next chapter.

Table 2.2 Summary of contemporary wind generator ELCAs reviewed

Wind Generator ELCA Literature	Aims and Objectives	Results
Al-Behadili and El-Osta (2015)	– The goal was to estimate the emissions and fuel consumption from 37 wind generators of 1.65 MW total capacity. – The functional unit was the generation of 1 kWh of electricity from wind generators. – The system boundary included the manufacturing of wind generator components, transport to wind farm, installation, commissioning, operation, maintenance and dismantling stages.	– The operational stage has negligible environmental impacts as compared to the other stages. – The study confirmed that wind energy generation emits less CO_2, NO_x and SO_2 and consumes less fuel per kWh power production in comparison with a fossil fuel plant.
Ardente et al. (2008)	– The aim was to evaluate the life cycle environmental impacts of a wind farm in Italy. – The functional unit was defined as the generation of 1 kWh of electricity. – The system boundary covered the wind generator manufacturing, installation, transport, operation, maintenance, decommissioning and disposal stages.	– Equipment manufacturing was the most emission intensive stage (61%) followed by building works construction (32.5%), operation and maintenance (6.4%) and decommissioning (1.7%). – The impacts associated with these stages consist of air emissions that contribute to global warming potential, ozone depletion, acidification, photochemical ozone creation and eutrophication.
Demir and Taşkın (2013)	– The goal was to evaluate the environmental impacts of the wind generators in Turkey. The analysis consisted of three medium sized (330 kW, 500 kW, 810 kW) and two large sized (2,050 kW and 3,020 kW) wind generators. The wind generators were compared based on their EPBT and environmental impacts including acidification, eutrophication, global warming potential, freshwater exotocicity, human toxicity, photochemical oxidation creation and terrestrial ecotoxicity.	– The environmental impacts from the generation of electricity using wind generators are less than the impacts of an equivalent fossil fuel technology. – Environmental improvement strategies such as optimisation of wind speed generation, use of alternative generator materials and increased material recycling rates can reduce the overall environmental impacts. – The EPBT of the analysed wind generators ranged from 14.6 to 35.6 months.

Wind Generator ELCA Literature	Aims and Objectives	Results
	– The functional unit of the ELCA was 1 kWh of electricity delivered to the power grid. The operational life of the wind generators was assumed to be 20 years. – The system boundary considered the whole lifespan of the wind generators encompassing material extraction to recycling stages.	
Garrett and Rønde (2013)	– The goal was to assess the life cycle environmental impacts associated with electricity generation of a 50 MW onshore wind farm. – The functional unit was 1 kWh of electricity delivered to the grid. This analysis was based on the 20 year lifetime design of the wind generator. – The system boundary included the production of wind generator components, transport, installation, operation and end-of-life disposal stages.	– The manufacturing stage contributed the largest share to all environmental impacts. The impact contribution came from the manufacturing of the tower (25 – 30%), cables (20%), nacelle (15%), blades (10 – 15%) and foundations (10%). The operational stage contributed only 3% to all environmental impacts. – Metal recycling has 30% potential environmental credit.
Glassbrook et al. (2014)	– The goal was to assess the global warming potential and embodied energy of electricity generation using 400 W, 2.5 kW, 5 kW and 20 kW wind generators. This ELCA study also compared the environmental impacts to that of an equivalent diesel system. – The functional unit was the generation of 600 kWh of electricity per year. The operational life span of the wind generator was 20 years. – The system boundary covered extraction of raw materials, generator manufacturing, transportation, operation, maintenance and disposal stages.	– Larger wind generators were found to have higher global warming potential and embodied energy than smaller generators. These were attributed to large quantity of concrete foundation and bigger towers used to support these higher capacity generators. However, larger wind generators have less environmental impact intensity when considering the impact per unit of rated capacity. – The comparative analysis shows that global warming potential and embodied energy of wind generators were lower than diesel generators.
Guezuraga et al. (2012)	– The aim was to estimate the primary energy consumption and GHG emissions of a 2.0 MW wind	– The largest environmental impacts came from the wind generator production (84%) and generator transport (7%).

Wind Generator ELCA Literature	Aims and Objectives	Results
	generator with gearbox and a 1.8 MW wind generator without gearbox. – The functional unit was the generation of 5.98 GWh and 3.27 GWh of electricity per year for the 2.0 MW and 1.8 MW wind generators. The operational lifespan of the wind generators were 20 years. – The system boundary considered the entire life cycle of the system from manufacturing the components to decommissioning.	The operation stage contributes only 1.2% of the total impacts. Further investigation of the hotspot shows that tower, nacelle and foundation contributed most of the impacts as attributed to the large quantity of steel required. – Recycling of materials was analysed and shown to reduce the raw material requirements. This consequently reduced the primary energy requirement by 43% and GHG emissions by 44%.
Kabir et al. (2012)	– The aim was to determine a 100 kW_p wind generator configuration in Canada with the least energy and environmental impacts. – The functional unit was 1 kWh of nameplate electricity generation. The life time of the wind generators were assumed to be 25 years. – The system boundary covered wind generator production, transportation, installation, operation, maintenance, decommissioning, recycling and disposal stages.	– The production of wind generator components had the highest primary energy consumption and environmental impacts among the life cycle stages. – The study found that the production of bigger wind generators has greater environmental advantage than producing smaller wind generators.
Oebels and Pacca (2013)	– The goal was to assess the GHG emissions in the electricity generation of a theoretical wind farm in Brazil with fourteen 1.5 MW wind generators. – The functional unit was defined as the generation of 1 kWh of electricity delivered to the grid. – The system boundary considered material processing, manufacturing, construction and operational stages. The dismantling and disposal stages were excluded, as no	– The production of wind generator components contributed the largest emissions (93.8%) followed by the transportation stage (5.6%). The contribution of the wind generator construction and operational stages were found negligible. – In the production stage, the tower constituted half of the environmental impacts due to the large amount of steel used followed by the foundation (20%), nacelle (16%) and blades (10%).

Wind Generator ELCA Literature	Aims and Objectives	Results
	entity in Brazil have yet created or invested for disposal treatment of wind generators.	– Replacing the steel tower with concrete tower reduced the environmental impacts by 6.4%.
Rashedi et al. (2013)	– The goal was to evaluate the life cycle environmental impacts of a 50 MW horizontal axis wind generator in terms of end-point impact categories (human health, ecosystem quality, resources). – The functional unit was defined as the production of a 50 MW generator.	– Steel constitutes the largest share of material in the production of wind generators. – Copper had the largest environmental impacts, which are 27.45 times higher than steel. – The replacement of steel to aluminium alloy demonstrated 30% environmental impact reduction. – Concrete tower design was suggested to replace existing steel towers, as it can significantly reduce environmental impacts.
Tremeac and Meunier (2009)	– The aim was to assess the life cycle environmental impacts of a 4.5MW and 250 W wind generators in France. Four damage categories were assessed including climate change, resources, ecosystem quality and human health. – The functional unit was the generation of 1 kWh of electricity over 20 years. – The system boundary covered the production of wind generator components, construction, operation and decommissioning stages.	– The production of wind generators had the highest contribution to all environmental impacts followed by transport. The operational stage was found to have negligible impact (<7%). – For the 250W wind generator, the recycling of materials can offset the operation and construction stages.
Uddin and Kumar (2014)	– The goal was to assess the life cycle environmental impacts and energy consumption of vertical and horizontal axis wind generators. – The functional unit was defined as the generation of 1 kWh of electricity. – The system boundary involved raw material extraction, manufacturing of wind generator components,	– The production of wind generator components had the highest primary energy consumption (75%) due to the energy intensive production of aluminium and steel. – The energy required for the operation and disposal is considered negligible. – The production of wind generator components was also the most environmental intensive stage.

Wind Generator ELCA Literature	Aims and Objectives	Results
	transportation, installation, use, disassembly and disposal stages.	– The replacement of aluminium with fibreglass can reduce primary energy consumption by 40% and global warming potential by 22%.
W. C. Wang and Teah (2017)	– The goal was to estimate the life cycle environmental impacts of a horizontal wind axis generator in terms of global warming potential and primary energy production. – The system boundary included the acquisition of raw materials to eventual disposal.	– The raw material acquisition and wind generator production were the largest contributor to global warming potential (70%) and primary energy consumption (99%) followed by transport and disposal.
Y. Wang and Sun (2012)	– The aim of the ELCA was to estimate the amount of GHG emissions released per kWh of electricity generated. This study analysed three wind generators in China including a 1.65 MW Vestas V82, 3.0 MW Vestas V90 and 850 kW Vestas V52. – The system boundary covered the production of the wind generator components, transportation, operation and disposal stages.	– The production of wind generator components contributed 98% to the overall GHG emissions followed by the transport stage. The operational stage has a negligible impact. – The comparison among different wind generator sizes showed that higher capacity has less GHG emissions due to economies of scale. –
Xu et al. (2017)	– The goal of the study was to evaluate the life cycle environmental impacts of a typical wind power generator in China. – The functional unit was the generation of 1 kWh of electricity over 20 years. – The system boundary included the production of wind generator components, operation, maintenance, disassembly and disposal stages.	– The production of wind generator components contributed the largest to all environmental impacts (56%). – The environmental impacts from the installation, operation and transportation stages have minimal influence.

2.5.1.3 Review of environmental life cycle assessment (ELCA) of hybrid systems

The review of previous studies on ELCA of fossil fuel-renewable hybrid systems has been summarised in Table 2.3. These studies provide a comparative analysis of various power generating technologies, which mostly use solar PV and wind hybrid systems. The lessons and information acquired from the aforementioned review of hybrid system ELCAs was considered in this study.

Most of these ELCAs have estimated a number of environmental impacts to determine the extent of environmental damage caused by generating electricity using hybrid systems. Schofield (2011) characterised these impacts in terms of abiotic depletion, acidification, eutrophication, global warming potential, ozone layer depletion, photochemical ozone creation, while Sevencan and Çiftcioğlu (2013) and Petrillo et al. (2016) classified them as human, environment and resource damage categories. The LCIs of ELCAs were calculated based on a functional unit and was defined as generating electricity to load demand over an operational life of 20 to 25 years. The system boundary in all these ELCAs was comprised of acquisition of raw materials, manufacturing of the power generating equipment, transportation, installation, operation and maintenance and disposal stages.

Similar to the solar PV and wind generator ELCAs, hotspot analysis was conducted to determine the life cycle stage that causes the greatest impact. Unlike solar PV and wind, these ELCAs show that the operational stage (combustion of diesel) is responsible for the majority of environmental impacts (Petrillo et al., 2016; Smith et al., 2015). These studies suggest that the electricity generated from RETs in the hybrid system does not completely offset the environmental impacts from the combustion of fossil fuels. Strategies were implemented in this current study to increase renewable energy penetration in a hybrid system to improve environmental performance.

The ELCAs show that the integration of RETs in diesel only systems can potentially reduce environmental impacts. However, the integration of RETs is constrained by its high capital cost (Allan et al., 2015). Further review has been conducted to consider the economic implications of these environmentally friendly technologies.

Table 2.3 Summary of contemporary hybrid system ELCAs reviewed

Hybrid System ELCA Literature	Aims and Objectives	Results
Smith et al. (2015)	– The goal was to evaluate the potential life cycle environmental impacts of a diesel/PV/wind microgrid in Thailand and to compare these impacts with that of a home diesel generator and central grid extension. – The functional unit was defined as generating 265 kWh of electricity per day in Koh Jig, Thailand for 20 years. – The system boundary considered relevant to the study were raw material acquisition, manufacturing, and transportation of components, use and disposal stages.	– The combustion of diesel in the microgrid constituted the largest to the total global warming potential (84%), abiotic resource depletion (60%) and acidification (53%), while the mining to manufacturing stages contributed the largest to human toxicity. – The result of the comparative analysis shows that the microgrid is lowest in global warming potential, abiotic resource depletion and human toxicity.
Sevencan and Çiftcioğlu (2013)	– The goal was to compare the life cycle environmental impacts of an existing electricity generation system for a mobile house and various alternative generating options. – The functional unit was defined as electricity generation for one year. – The system boundary encompassed material extraction to disposal stages.	– Wind generators had the least environmental impact due to high recyclability rate of its components than solar PV. – Diesel generator was the most environmentally friendly backup power source. Fuel cells were not considered a good option due to its energy intensive materials.
Schofield (2011)	– The goal was to compare the life cycle environmental impacts of a wind-diesel hybrid system in comparison with a diesel system. – The functional unit was defined as generating electricity to remote areas in Canada for 20 years. – The system boundary included the extraction of raw materials, manufacturing of diesel generator and wind generator, their transportation to site, use stage, disassembly and ultimate disposal.	– The hybrid system had lower environmental impacts than the diesel system. – The normalised environmental impacts show that global warming was the largest contributor to all impacts followed by abiotic depletion.

Hybrid System ELCA Literature	Aims and Objectives	Results
Petrillo et al. (2016) Turkey	– The aim was to compare the environmental performance of three hybrid power supply system for a mobile telecommunication station. – The functional unit was the operation of the power supply options for one year. – The system boundary included the extraction of raw materials, manufacturing of the components and use stages.	– The diesel generating system had poor environmental performance in most impact categories due to the consumption of fuel. The two hybrid alternatives had high ecotoxicity impacts due to the toxic chemicals used for the energy storage system.

2.5.2 Life cycle costing

The economic factor is fundamental in strategic decision making processes (Australian National Audit Office, 2011; New South Wales Treasury, 2004; Wübbenhorst, 1986). Life cycle costing (LCC) is an effective economic tool that assists in the analysis of the revenues and costs over the entire life cycle of products or services (Fan, 2014; Vlachý, 2014; Woodward, 1997). This economic approach also allows decision makers to be conscious of significant cost parameters and assists in identifying strategies to minimise these costs (Ally & Pryor, 2016; Laura & Vicente, 2014).

The scope of LCC has been recently extended to include socio-economic externalities, system effectiveness and environmental costs in addition to the traditional capital and operating costs (Sherif & Kolarik, 1981). Hannouf and Assefa (2016) described the importance of LCC in sustainability assessments and asserted that sustainable products must not only be environmentally beneficial and socially equitable but also economically feasible. Therefore, constraining one of the sustainability pillars may undermine the selection of a sustainable solution.

The application of LCC in power generating technologies can help formulate comprehensive energy policies and discern valuable decisions (Soni, Dash, Singh, & Banwet, 2014). For example, NREL (2013) suggested the effectiveness of LCC in providing key information for selecting power generating technologies in the US. In eco-efficiency, LCC is an appropriate method to be used in parallel with ELCA (Huppes & Ishikawa, 2005; Kicherer et al., 2007; Saling, 2016). K. Lawania and Biswas (2016) demonstrated the effectiveness of using LCC with ELCA in developing a life cycle management (LCM) framework for building sustainability assessment.

2.5.2.1 Review of life cycle costing studies of energy technologies

A LCC of power generating technologies that were published over the last 10 years has been summarised in Table 2.4. Based on the nature of current research, the review only considered those literatures that included both LCA and LCC analyses for determining cost-effective environmentally friendly options. These LCC studies were conducted in both developed and developing countries for a wide range of RETs and hybrid systems.

The majority of the LCC studies were conducted in parallel with an ELCA to determine both the economic and environmental implications of power generating technologies (Kannan et al., 2006; Petrillo et al., 2016). The same functional unit and system boundary with the ELCA must be used in the LCC to maintain consistency of analysis. The system boundary of these LCC studies has considered the equipment acquisition, installation, operation and maintenance, dismantling and disposal stages (Fan, 2014; Laura & Vicente, 2014; Marszal, Heiselberg, Lund Jensen, & Nørgaard, 2012; Perera, Attalage, Perera, & Dassanayake, 2013; Petrillo et al., 2016).

The reliability of the LCC results is highly dependent on the sources of the life cycle cost inventory. Most information in these studies has been sourced from project contractors and records of manufacturers (Fan, 2014; Petrillo et al., 2016). When project specific costs were not available, engineering cost estimation was conducted to estimate these costs (Abbes, Martinez, & Champenois, 2014; Kannan et al., 2006; Perera et al., 2013).

The net present value (NPV) parameter in LCC is widely used for evaluating and comparing the cost-effectiveness of different power generating technologies (Abbes et al., 2014; Laura & Vicente, 2014; Palanisamy, 2013; Perera et al., 2013). Various discount rates have been used in these LCC studies to calculate the NPV. Since the percentage distribution of cost in each life cycle stage is sensitive to the discount rate (Kannan et al., 2006; Marszal et al., 2012), sensitivity analysis can be conducted.

The results of the studies varied due to differences in LCC objectives. The LCC of solar PVs and wind generators has shown that the capital cost constituted 53% to 96% of the total life cycle costs, while the LCC of hybrid systems has shown that the integration of RETs can reduce the total life cycle cost due to reduction of fossil fuel cost. Further research has now been conducted to determine the social implications of these environmentally friendly power generating technologies.

Table 2.4 Summary of contemporary power generation technology LCCs reviewed

LCC Literature	Aims and Objectives	Results
Abbes et al. (2014)	– The goal was to develop a framework to minimise the embodied energy, life cycle cost and loss of power supply probability of a PV/wind/battery hybrid system. – The system boundary of the LCC included the design to the recycling of system components. – The LCC calculation was based on 5% discount rate, 2% inflation rate and 25 years lifetime.	– The framework was applied to the PV/wind/battery design of a residential house. The multi-objective optimization framework could be beneficial for decision support in the selection of components for off-grid electricity generation.
Akyuz, Oktay, and Dincer (2011)	– The goal was to compare the life cycle cost of four systems including diesel, solar PV/diesel/battery hybrid, wind/diesel/battery hybrid and solar PV/wind/diesel/battery hybrid systems for on-grid residential use.	– The cost of fuel had the largest effect on the system life cycle cost. The solar PV/wind/diesel/battery system had the least cost among other systems due to less dependence on diesel power production. – The life cycle cost of each option was found to be sensitive to diesel prices.
Fan (2014)	– The goal was to evaluate the economic feasibility of a rooftop solar PV system in Colorado. – The system boundary included capital cost (acquisition, transport and installation), operation cost (cleaning of the solar modules and replacement of batteries) and recycling cost.	– The capital cost constituted 92% of the overall life cycle cost followed by the replacement of inverters and batteries.
Kannan et al. (2006) Singapore	– The aim was to evaluate the cost implications of a 2.7 kW_p solar PV system consisting of 36 mono-Si modules constructed in Singapore. A parallel ELCA study to quantify primary energy consumption and GHG emissions was also conducted. The system boundary included capital, maintenance and decommissioning costs. No operational cost was recorded since solar PVs were assumed to not consume	– The capital cost contributed 96% of the total life cycle cost. – The total life cycle cost was found to be sensitive to discount rates. – The life cycle cost of the solar PV system was found to be eight times higher than an equivalent oil-fired power plant.

LCC Literature	Aims and Objectives	Results
	fuel. The maintenance of the system was assumed to be a fortnightly cleaning of the modules.	
Laura and Vicente (2014)	– The goal was to determine the cost intensive process of an off-shore wind farm to determine measures to minimise the total life cycle cost. Three typical floating off-shore wind platforms were assessed. – The system boundary included the definition, design, manufacturing, installation, exploitation and dismantling costs.	– The percentage of the costs for all platforms (e.g. semisubmersible platform, tensioned leg platform and spar platform) shows that the manufacturing cost accounted the significant portion of the total life cycle cost (53% to 63.6%) followed by maintenance cost (24.5% to 30.9%) and installation cost (5.3% to 16.1%).
Marszal et al. (2012)	– The goal was to determine the life cycle cost of a renewable energy supply system for a newly built net zero energy building. – The system boundary encompassed investment, operation and maintenance, replacement and decommissioning costs.	– The use of RETs in off-grid buildings can help achieve a cost optimal path towards net zero energy buildings. – The life cycle cost was found to be sensitive to interest rates.
Perera et al. (2013)	– The aim was to develop a multi-objective optimisation framework in the selection of power generating technologies for standalone applications. LCC was used to analyse the costs of the hybrid energy systems. – The system boundary included acquisition, installation, and operation and maintenance costs. Net present value (NPV) was used to calculate the cash flow over the operational life of the system.	– The framework was found to be beneficial in modeling and simulating hybrid energy systems. – The life cycle cost was also found to be sensitive on diesel prices.
Petrillo et al. (2016)	– The goal was to develop a systematic method to select appropriate power generating technologies using life cycle thinking. This study used LCC to assess the economic costs of a mobile telecommunication station. – The system boundary included acquisition, installation, operation, maintenance and decommissioning costs.	– The operational stage of the alternative power generating technologies had the highest share (46 to 54%) in the overall life cycle cost followed by the maintenance and capital costs.

2.5.3 Social life cycle assessment

The United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) guidelines are the only existing method published for conducting SLCA of products (UNEP & SETAC, 2009). This focuses on the social dimension of sustainable development in decision-making processes (Finkbeiner, Schau, Lehmann, & Traverso, 2010). SLCA has been applied in various studies including the food industry (Albrecht et al., 2013; Bouzid & Padilla, 2014; De Luca, Iofrida, Strano, Falcone, & Gulisano, 2015; Feschet et al., 2013), waste disposal methods (Aparcana & Salhofer, 2013a, 2013b; Foolmaun & Ramjeeawon, 2013; Hu, Kleijn, Bozhilova-Kisheva, & Di Maio, 2013), bioenergy (Macombe, Leskinen, Feschet, & Antikainen, 2013; Manik, Leahy, & Halog, 2013; Ren, Manzardo, Mazzi, Zuliani, & Scipioni, 2015) and construction (Hosseinijou, Mansour, & Shirazi, 2014). However, SLCA has only been applied in a few power generation studies.

The review of SLCA studies of power generating technologies is summarised in Table 2.5. The studies conducted include the assessment of the social implications of solar PV technologies and comparative SLCA analysis of different power generating technologies worldwide. The main stakeholder considered by the majority of these studies is the 'worker', while the most commonly used social indicators evaluated are local employment, wage and employment health and safety. Yu and Halog (2015) have included a variety of stakeholders (e.g. manufacturers, government, electricity distribution network) to provide a more comprehensive SLCA analysis.

An assessment using SLCA is flexible since no specific rule (e.g. selection of stakeholders and social indicators) was proposed in the UNEP and SETAC guidelines, (Schlör, Zapp, Marx, Schreiber, & Hake, 2015). However, this could result in a lack of meaningful comparison between studies due to a variability in the rules followed (Traverso, Asdrubali, Francia, & Finkbeiner, 2012; Yu & Halog, 2015). Despite this limitation, SLCA can potentially be integrated with ELCA and LCC to create a Triple Bottom Line (TBL) approach for a comprehensive sustainability assessment.

Table 2.5 Summary of contemporary power generation technology SLCAs reviewed

SLCA Literature	Aims and Objectives	Results

Atilgan and Azapagic (2016)	– The goal of the study was to evaluate the social implications of the Turkish electricity sector.
	– The functional unit was 1 kWh of electricity generated in Turkey. The scope considers a cradle-to-grave approach comprising of material extraction, transportation, construction, operation and decommissioning.
	– The social indicators considered are the provision of employment, worker safety and energy security.
	– The power generating technologies for comparative analysis were lignite, hard coal, gas, large hydro reservoir, small hydro reservoir, run-of-river, wind and geothermal.
		– The summary of the SLCA were listed as follows.
		  – Run-of-river hydropower had the highest life cycle employment but it caused the highest injuries and accident-related fatalities.
		  – Lignite and hard coal power technologies had the highest injuries and fatalities due to fuel mining.
		  – Large reservoir hydropower offered the least injuries and fatalities but had the lowest life cycle employment.

Traverso et al. (2012)	– The goal was to assess the social implications of different PV modules (e.g. German multi-Si modules in 2008 and 2009, and Italian multi-Si modules in 2008) using a set of social indicators. – The social indicators used were child labour, wages, social benefits, health conditions, working hours and discrimination. – The functional unit used in the case study was the production of 1 m^2 of modules. – The system boundary were selected based on their relevance to the social indicators.	– The German module 2009 was found to have the least social benefit for both of minimum and average wage rating and working hours. The reason for this is due to the crisis experienced in 2009 that required the company to focus more on economic performance.
Yu and Halog (2015)	– The goal was to assess the social implications of a 1.2 MW solar PV panels in Queensland from the perspective of various stakeholders.	– The study found that the solar PV system had positive impacts on local employment.

SLCA Literature	Aims and Objectives	Results
	– The functional unit was the generation of 1 kWh of electricity. The system boundary considered all the stakeholders (e.g. manufacturer, Queensland government and electricity distribution network) involved during raw material extraction, material processing, product manufacturing, installation, operation, maintenance and disposal stages. – Various social indicators were assessed including health and safety, contribution to technology development and research collaboration, local employment and community engagement.	– The generation of electricity from solar PV does not have serious adverse social impacts but this could bring concerns with health and safety problems due to end-of-life treatment in the future.

2.5.4 Triple bottom line analysis

A triple bottom line (TBL) approach integrates the three pillars of sustainability into a sustainability assessment by reviewing the adverse effects of economic activities on society and environment (Ozgun et al., 2015). This concept was first discussed by John Elkington in 1994 when he stated that a business should consider people, planet and profit in decision-making processes (Jackson, Boswell, & Davis, 2011). In the energy sector, TBL has been used to evaluate the sustainability performance of power generating technologies for comparative purposes. The review of previous TBL studies of power generating technologies is summarised in Table 2.6.

The TBL studies reviewed included the assessment of the sustainability performance of RETs and a comparative analysis of various technologies for RAPS and on-grid power generation. The majority of these studies follow the ELCA guidelines from ISO 14040-44 to conduct an environmental assessment, while the SLCA guidelines by UNEP and SETAC were followed for social impact assessment. LCC and various cost methods were followed to conduct an economic assessment. Several approaches were followed in conducting sustainability assessment. Petrillo et al. (2016) developed a Relative Sustainability Index (RSI) to generate a single value indicator, whereas the majority of the studies used Multi-Criteria Decision Analysis (MCDA) to generate sustainability scores (Bewley & Schneider, 2013; Tianqi Li, Roskilly, & Wang, 2017; Petrillo et al., 2016).

Although TBL is an effective tool to determine the sustainability performance of power generating technologies, the lack of definitive guidelines to assess economic and social implications and to integrate the environmental, economic and social results was found to be limiting (Tianqi Li et al., 2017). A tool that can help in the selection of a cost-effective and environmentally friendly RAPS option is therefore required. Eco-efficiency analysis (EEA) is a well-developed concept that can assist with this, but it does not consider social aspects.

Table 2.6 Summary of contemporary power generation technology TBL reviewed

TBL Literature	Aims and Objectives	Results
Atilgan and Azapagic (2016)	– The goal was to assess the life cycle sustainability assessment (LCSA) of the electricity sector in Turkey considering the economic, environmental and social implications of power generating technologies. – The functional unit was the generation of 1 kWh of electricity in Turkey. – The system boundary considered a cradle-to-grave approach including material extraction, transportation of materials, construction, operation and decommissioning stages. – Multi-criteria decision analysis (MCDA) was used to integrate the three pillars of sustainability. This was conducted assuming equal importance of the indicators and then a sensitivity analysis was carried out assuming different weighting.	– Hydropower was the most sustainable technology followed by wind and geothermal. Lignite is the least sustainable technology and this was attributed to its poor environmental performance. – The ranking of the power generating technologies varies with the weighting of each sustainability pillars.
(Tianqi Li et al., 2017)	– The goal was to assess the LCSA of the three commonly used solar PV in England including mono-Si, multi-Si and CdTe panels. – Indicators were selected for the three pillars of sustainability including environment, techno-economic and social. ELCA was used to evaluate the environmental indicators, while various methods and tools were used to assess the economic and social indicators. – The system boundary included the manufacturing of the equipment, installation, operation and disposal stages.	– The study found that the multi-Si PV was the most sustainable option among other solar PV technologies. It was suggested that the sustainability performance of these technologies can be improved with advancement in the future.

TBL Literature	Aims and Objectives	Results
Petrillo et al. (2016)	– The goal was to develop a Relative Sustainability Index (RSI) for a stand-alone hybrid renewable energy system of a radio station using different scenarios (e.g. diesel generator, solar PV-diesel hybrid, solar PV-fuel cell hybrid). Analytical hierarchy process (AHP) was used to generate relative sustainability values. – The sustainability pillars environment, economic and social were evaluated using ELCA, LCC and SLCA, respectively. – The functional unit was the operation of the power supply system for one year. – The system boundary covered extraction of raw materials, manufacturing of equipment and use stages.	– The RSI represented a single index that aggregates the weights of each sustainability pillar and their subcriteria. The weighting was deduced to affect the significance of the results due to potential bias in scoring. – The hybrid systems were found to be a more sustainable energy solution due to higher index values, which were attributed to better social and environmental performance.
Traverso et al. (2012)	– The goal was to assess the LCSA of solar PV panels (e.g. German multi-Si PV in 2008 and 2009, Italian multi-Si PV in 2008) by considering the environmental, economic and social pillars of sustainability. – The indicator values were entered in a software to rank all the options. In the first application, the same weight was assigned to all indicators and then various weights were assumed for sensitivity analysis. – The functional unit was 1 m^2 of solar PV panels.	– The results revealed that the 2008 German solar PV panels was the most sustainable option, while the 2008 Italian solar PV panel was the least sustainable option.
Yu and Halog (2015)	– A LCSA was conducted for a 1.2 MW roof mounted solar PV array (UQ solar) in Queensland. – The environmental, economic and social implications were evaluated using ELCA, LCC and SLCA, respectively. – The functional unit was the generation of 1 kWh of electricity.	– The results show that UQ Solar had high environmental and economic performance. Although the social implications of UQ Solar is not high, there were no adverse impacts found.

2.5.5 Eco-efficiency analysis

Eco-efficiency is a sustainability concept that seeks to increase economic progress through efficient use of natural resources. This combines two of the three components of sustainability assessment, economics and environment (Eherenfeld, 2005). In 1989, the concept of eco-efficiency was first discussed by Schaltegger and Sturn and was then recognised by the World Business Council for Sustainable Development (WBCSD) through a report titled *Changing Course* (Cope, 1993; Verfaillie & Bidwell, 2000) . They defined the concept of sustainable development as, "achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least within the earth's estimated carrying capacity."

Businesses managers and stakeholders are expected to use eco-efficiency to achieve economic and environmental progress. This was also expected to be used as a leverage for businesses to get more involved in environmental policy (Barrington, 2000; Cope, 1993).

Valuable changes in a business operation have to be met by companies to achieve eco-efficiency. The practical application of eco-efficiency requires innovation to be applied in creating more production value with lower material and energy inputs and less emissions. This can be potentially met through demonstration of any of the seven eco-efficiency objectives including the reduction of material intensity, energy intensity and dispersion of toxic substances, enhancement of recycling, maximisation of renewables, extension of product life and increase in service intensity (Verfaillie & Bidwell, 2000). WBCSD proposes the application of eco-efficiency not only in the initial stage of a business but also across the entire operation.

Measuring eco-efficiency is performed by taking the ratio of an output and an input (Saling, 2016). This kind of indicator often uses monetary value or production value as a useful input, while the reduction in resource use and emissions can be used as a valuable output. This can illustrate the relationship between environmental degradation and production value. This concept is similar to the decoupling of economic growth from environmental degradation as discussed by UNEP (2011). The contribution of these indicators includes presentation of simplicity in measurement and facilitate understanding for business stakeholders unacquainted with environmental problems. However, none have clearly shown eco-efficiency as a method that links economic and environmental issues for the improvement of production value.

Recently, an eco-efficiency assessment tool linked to ISO 14045 (ISO, 2012) has been developed for quantitative assessment of production values and life cycle environmental impacts of a production system. This follows the same life cycle thinking perspective of ISO 14040 (ISO, 2006) to evaluate environmental impacts. The chemical production company BASF developed a method of eco-efficiency assessment for the selection of options and alternative processes (Eherenfeld, 2005). Their method evaluates economic and environmental values for the same functional unit and considers a cradle-to-grave approach (Kicherer et al., 2007). Several studies have been conducted since then to determine strategic options for system optimisation, identify improvement potentials for products and processes and support communication with decision makers, researchers and consumers (Saling et al., 2002). These studies include assessment of indigo processing, mineral water beverage packaging (Saling et al., 2002), ultraviolet curing (Shonnard et al., 2003), vitamin B2 production, astaxanthin production (Saling, 2005), textile dye works, transportation logistics (Wall-Markowski, Kicherer, & Wittlinger, 2005) and asphalt road preservation (Uhlman & Saling, 2010). This method can also be used to explore potential for eco-efficiency improvement in RAPS systems.

2.5.5.1 Eco-efficiency analysis of RAPS in Western Australia

Most research studies have suggested that the eco-efficiency analysis of power generating technologies with an emphasis on its environmental and economic implications could be a valuable tool for identification of appropriate power generating technologies (Arabi, Munisamy, Emrouznejad, & Shadman, 2014; Athanassopoulos, Lambroukos, & Seiford, 1999; Burchart-Korol, Krawczyk, Czaplicka-Kolarz, & Smoliński, 2016; Burnett & Hansen, 2008; Korhonen & Luptacik, 2004; Liu, Chu, Yin, & Sun, 2017; Sarıca & Or, 2007; Sözen, Alp, & Kilinc, 2012). In addition, this research considers the implementation of appropriate eco-efficient strategies for RAPS systems.

An eco-efficiency analysis (EEA) framework has been developed in this research to integrate ELCA and LCC (Appendix A). In comparison with a triple bottom line approach, EEA does not consider the social implications of electricity generation. The reasons for excluding the social objective are due to the fact that there is no consensus on the types of social indicators used for SLCA and the lack of international or Australian studies that provide information in normalising and weighting these social indicators. Whilst the social aspect of sustainability is not considered in the present study, the framework would assist in the implementation of improvement opportunities for the selection of environmentally friendly and economically viable power supply options.

2.6 Lesson Learnt and Research Gaps

This chapter reviews various sustainability tools including ELCA, LCC, SLCA, TBL and EEA. It was found that these approaches can be applied effectively in understanding the environmental, economic and social implications of RAPS technologies. Some literature on ELCA, LCC and SLCA approaches has shown that these methods have been used in the sustainability analysis of various products and services.

Research suggests that the operational stage during the life cycle of a renewable–diesel hybrid system has been found to contribute the largest environmental impacts. The ELCA approach assists in the determination of environmental impacts not only for the operational stage but also the impacts associated with mining to manufacturing of the power system equipment, their transportation to the site, construction, maintenance and eventual disposal. This approach also identifies environmental hotspots in which eco-efficiency strategies can be implemented to mitigate the environmental impacts. Since the integration of environmental improvement strategies may incorporate additional cost, a LCC approach should be used to evaluate the cost-effectiveness of the environmental mitigation strategies. The EEA enables the selection of an option that is equally environmentally friendly and economically viable.

Published literature suggests that no EEA framework has been developed for RAPS systems that could assist energy planners and policy makers not only to assess eco-efficiency but also to improve the eco-efficiency of these systems in the remote areas.

The EEA framework, which integrates the ELCA and LCC tools and the concept of eco-efficiency for RAPS is discussed in Chapter 3.

Chapter 3
Research Methodology

3.1 Introduction

This chapter presents the development of an eco-efficiency analysis (EEA) framework for assessing the techno-economic and environmental performance of remote area power supply (RAPS) systems in Western Australia. This framework includes a number of environmental management tools, including environmental life cycle assessment (ELCA), life cycle costing (LCC), eco-efficiency strategies and eco-efficiency portfolios. This chapter discusses the steps in addressing research Objective 1, which aims to develop a conceptual model for improving the eco-efficiency performance of RAPS systems in Western Australia.

Firstly, a conceptual model known as an "EEA framework" was discussed as to how the eco-efficiency performance of the existing RAPS systems can be compared using a range of life cycle management tools to find a cost-effective environmentally friendly or eco-efficient option(s). Secondly, an ELCA tool that follows ISO 14040-44 guidelines has been discussed as to how it assesses 15 environmental impacts in RAPS systems as part of the EEA framework. This ELCA also enables the development of a network flow chart to determine the breakdown of inputs and processes with the highest environmental impacts. Thirdly, this chapter discusses how the environmental improvement of these eco-efficiency strategies has been considered to treat the hotspots by generating improved RAPS options. Fourthly, a tool that was used for calculating the life cycle costs of both existing and improved RAPS options is discussed. Finally, it was discussed how ELCA and LCC results are utilised in calculating the eco-efficiency portfolio for comparing the eco-efficiency performance of both existing and improved RAPS options.

3.2 Eco-Efficiency Analysis Framework

3.2.1 Premises of an EEA Framework

The premises of the EEA framework are expounded as follows:

- Mandatory Renewable Energy Target (MRET): In Australia, almost 23.5% of national electricity demand is expected to be derived from renewable energy sources by 2020 (Evans & Peck, 2011). Power distribution utilities in the remote areas of Western Australia are expected to generate electricity from renewable energy technologies (RETs) to comply with the MRET (Hunt & Macfarlane, 2015).

- Fossil Dominant RAPS Systems: About 71% of remote communities serviced by Horizon Power in Western Australia generates electricity from diesel and gas (ARENA, 2014). This state houses 8,880 GWh or nearly two-thirds of the total Australian off-grid electricity demand. The electricity generated from conventional sources is expected to increase due to commitment of new exploration incentive schemes of Western Australian government. About 48 new exploration projects were awarded in 2017 (Department of Mines and Petroleum, 2015, 2016). This expansion of the electricity network would result in an estimated GHG emissions of 2.21 Mt CO_2 equivalent per year (ARENA, 2014). There are also emissions associated with the transportation of diesel and natural gas and some indirect impacts such as loss of biodiversity (Department of Environment, 2016).

- Economic Implications of Diesel Powered RAPS Systems: The proposition in the use of RETs in the off-grid electricity markets of Australia has also been intensified to reduce the risk of fuel price increase (ARENA, 2014). A substantial reduction in the fuel consumption of existing hybrid systems has not been achieved yet due to low renewable energy penetration.(ARENA, 2014). This compels to explore enabling technologies such as energy storage, cloud tracking and automatic communications and control to increase renewable energy penetration.

- EEA for RAPS Systems: The World Business Council for Sustainable Development (WBCSD) requires businesses to achieve economic success with reduction of material and energy intensity and maximised use of renewable resources (Verfaillie & Bidwell, 2000). Thus, it is worth investigating through this framework as to whether the increased use of renewable energy in RAPS could deliver long-term economic and environmental benefits.

- This conceptual model is proposed to find an alternative option for RAPS systems to offer electricity in a cost-competitive and environmentally friendly manner.

These elements provide important insight on the need of a framework to achieve an eco-efficient RAPS in Western Australia. An EEA framework that uses the life cycle approaches will endeavour to achieve the objectives of the current research.

3.2.2 Conceptual Model in Determining Eco-Efficient Options

An eco-efficiency analysis framework (Figure 3.1) was developed to address the first research objective. The author published this framework in Clean Technology and Environmental Policy in 2017 (Appendix A), which is loosely based on the concept developed by Saling et al. (2002) and Kicherer et al. (2007). The framework synergises the trade-off that exists between the economic and environmental objectives of sustainability and incorporates environmental life cycle assessment (ELCA), life cycle costing (LCC), eco-efficiency strategies and eco-efficiency portfolio analysis to select a power supply option, which complies equally to both economic and environmental objectives of sustainability.

The goal of the EEA framework is to help in the selection eco-efficient RAPS options. The essential components of this framework including life cycle assessment tools and eco-efficiency assessment could help to achieve this objective. The initial steps in this framework are to conduct an ELCA to estimate the life cycle environmental impacts of RAPS systems and identify the environmental hotspots. The outcome of this step is the generation of improved RAPS options (using eco-efficiency strategies) that treats the identified hotspots of the existing RAPS systems. Follow up ELCAs on the improved RAPS options are conducted to evaluate the potential environmental impact reduction. The next step then applies the LCC approach to estimate the net present value (NPV) of the existing and improved RAPS options.

After the LCC analysis, all environmental impacts are converted to a single value using normalisation and weighting processes, while the NPV is normalised with respect to the latest Australian gross domestic product (GDP). The normalised environmental impact and normalised cost values of the existing and improved RAPS options are utilised to form a two-dimensional diagram known as the eco-efficiency portfolio. Portfolio analysis of these options is performed to determine the most eco-efficient RAPS options.

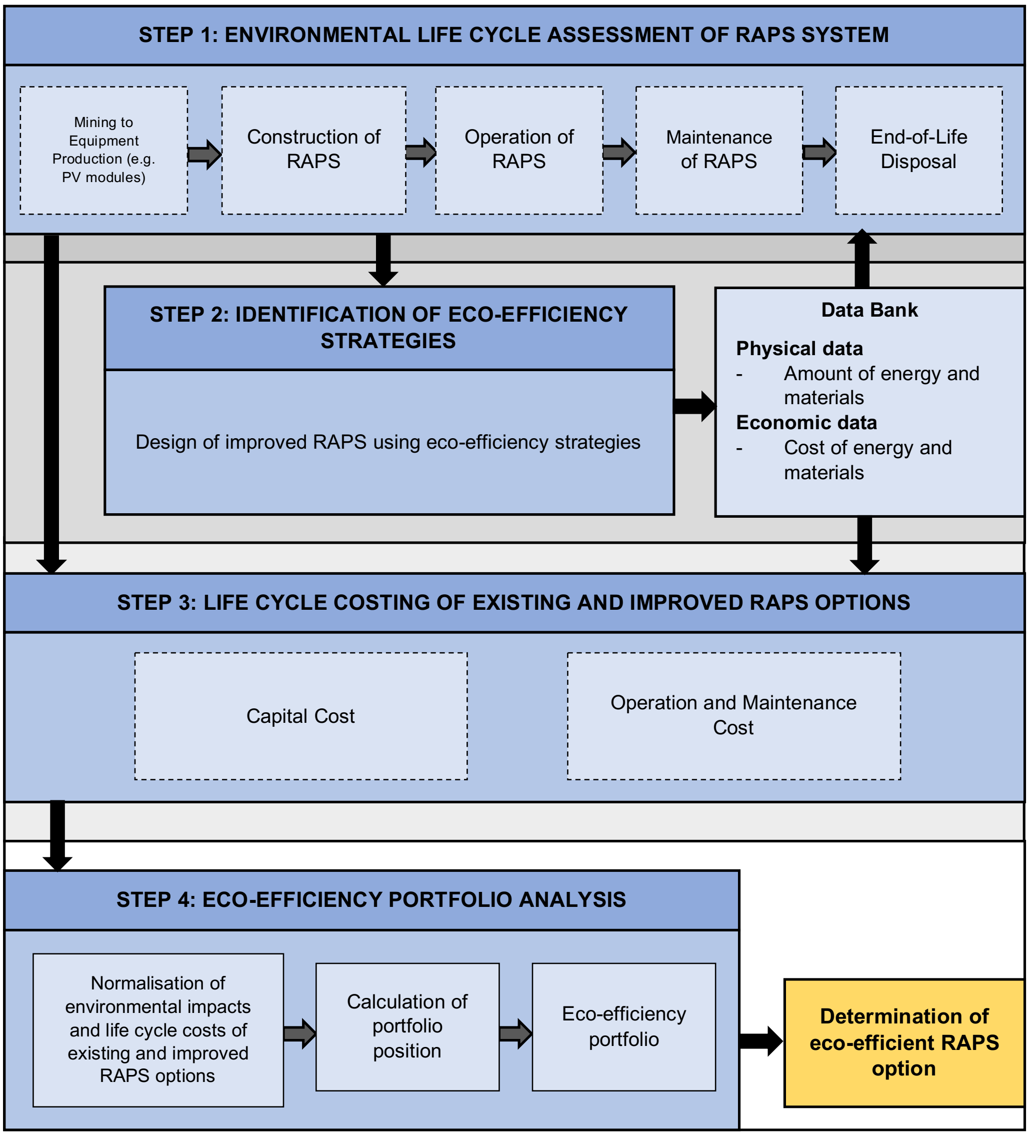


Figure 3.1 Flow diagram showing the eco-efficiency analysis (EEA) framework (Arceo et al. 2017)

3.2.3 Selection of Remote Area Power Supply (RAPS) Case Study Sites

Two case study areas have been selected to apply the EEA framework. Both coastal and inland areas generate electricity from a range of RAPS systems such as diesel, solar PV-diesel hybrid and wind-diesel hybrid systems. Since the intensity of solar radiation increases as it moves away from the coastal regions, solar PV technology has been considered for the electricity generation in inland areas in Western Australia. (Office of Energy, 2010). Conversely, coastal areas including the South Western Australia benefit from wind electricity generation (Office of Energy, 2010).

Despite abundant renewable energy resources in Western Australia, 100% deployment of renewable energy systems in remote areas is not feasible due to resource intermittency that causes fluctuations in system voltage and frequency (Anees, 2012; Evans & Peck, 2011; Holtmeyer et al., 2013). Hybridising renewables with fossil-fuelled generation has been found to reduce these risks (Allan et al., 2015).

Horizon Power, which is the sole supplier of electricity in the remote areas of Western Australia has thirty-five off-grid power supply networks (Figure 3.2). All these are dispersed across the state and the majority of the power supply networks are located in the Pilbara and Kimberley region. From thirty-five RAPS systems, three were selected in consultation with Horizon Power for inclusion in the analysis to represent the RAPS systems in Western Australia that utilise RETs and diesel engines for electricity generation.

Marble Bar and Yungngora represent a typical solar PV-diesel hybrid system, while Coral Bay represents a wind-diesel hybrid system. Both Marble Bar and Coral Bay power supply systems have been in operation since 2008 while Yungngora power supply system has been operating for only two years. Other RETs such as hydro, tidal and wave were not incorporated in the analysis. The reason for the exclusion is that there is no existing RAPS system in Western Australia that uses any of these renewable resources for electricity generation.

An agreement between Curtin and Horizon Power was made in order to access commercial information in confidence. In addition, Curtin University ethics approval was required prior to starting a survey for data collection.

Sections 3.3 to 3.6 show how the EEA framework can be implemented for assessment and determination of eco-efficient RAPS options in these three case study sites.

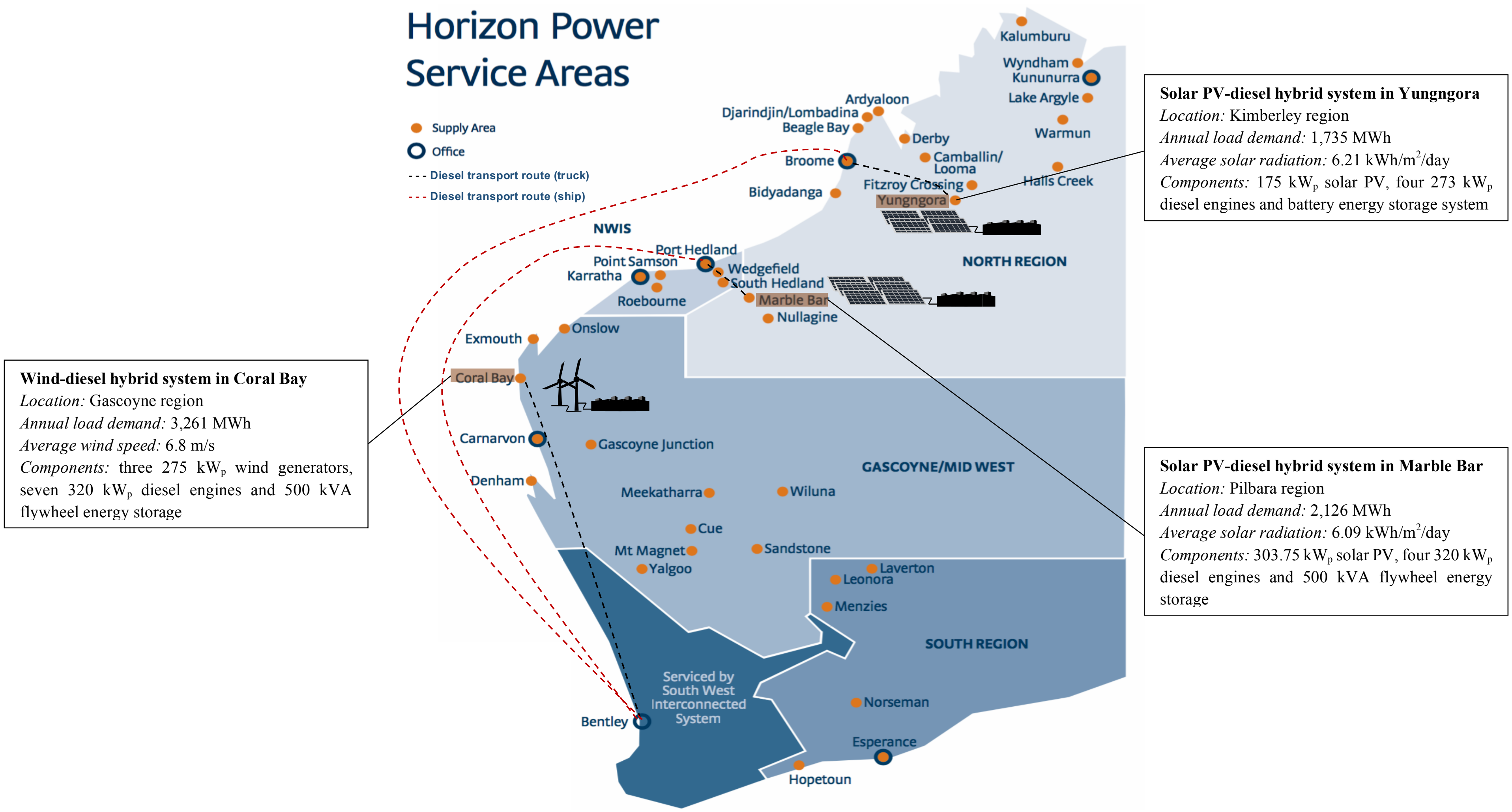


Figure 3.2 Three case study sites under Horizon Power service areas (ARENA, 2014)

3.3 Step 1: Environmental Life Cycle Assessment

The first step of eco-efficiency analysis requires the estimation of environmental impacts of the existing RAPS systems (Arceo et al., 2017; Saling et al., 2002; Verfaillie & Bidwell, 2000). In this research, the following relevant environmental impacts were assessed (Bengtsson & Howard, 2010a).

- Global warming potential
- Mineral depletion
- Fossil fuel depletion
- Land use and ecological diversity
- Water depletion
- Eutrophication
- Acidification
- Freshwater ecotoxicity
- Marine ecotoxicity
- Terrestrial ecotoxicity
- Photochemical smog
- Ozone depletion
- Ionising radiation
- Human toxicity
- Respiratory inorganics

These impacts have also been proposed to be used for consistent comparison among ELCA studies by the Building Products Innovation Council (BPIC) and AusIndustry (Bengtsson & Howard, 2010a). Environmental life cycle assessment has been used worldwide to estimate the environmental impacts associated with the production of various power supply technologies (Benton, Yang, & Wang, 2017; Chen et al., 2016; Fu et al., 2015; Hong, Chen, Qi, Ye, & Xu, 2016; Schofield, 2011; Smith et al., 2015; Spath et al., 1999; Zhong et al., 2011) and was considered as a tool for identifying an eco-efficient RAPS options in the EEA framework (Figure 3.3).

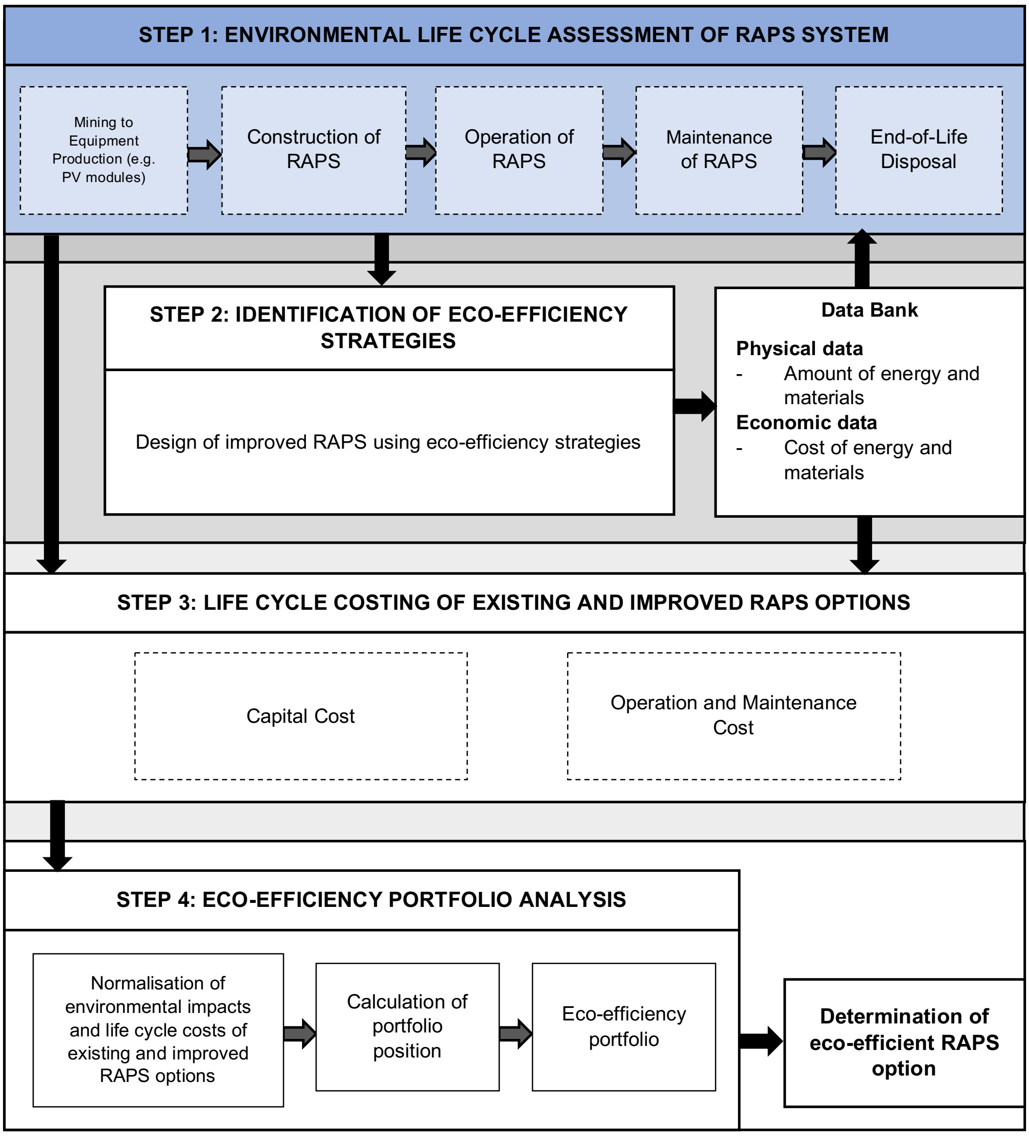


Figure 3.3 Environmental life cycle assessment part of the EEA framework

The four steps of ELCA that follow ISO 104040-44 guideline include goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation (ISO, 2006). The highlighted portion of Figure 3.3 presents the ELCA part of the EEA framework.

3.3.1 Goal and Scope Definition

The goal of an ELCA study provides a description of the proposed application and purpose of the study in order to facilitate decision making of intended stakeholders (Heijungs & Guinee, 2012; ISO, 2006). ELCA has been developed to estimate the environmental impacts associated with the electricity generation of RAPS. The life cycle stages which are identified as environmental hotspots are considered for further improvement using relevant and eco-efficient strategies.

The scope of the ELCA describes major details of the study to meet the defined goals (ISO, 2006). This defines in detail the system boundary considered for RAPS, the quality of data in representing the study and how the uncertainty in the data gathered can affect the overall analysis (Heijungs & Guinée, 2012). A functional unit (FU) determines the scope of the ELCA to develop a reference for the estimation of all the inputs and outputs involved in all life cycle stages of products or services. For comparative ELCA analysis, the FU provides a level of comparison among products or processes to eliminate the differences in the performance (Heijungs & Guinée, 2012).

The FU of the study is 1 MWh of electricity generation. Based on the operational life of the RETs and various global ELCA studies conducted for these technologies, the operational life cycles considered are 25 years for solar PV technologies and 20 years for wind technologies (Chen et al., 2016; Demir & Taşkın, 2013; Fu et al., 2015; Leopold; Schofield, 2011; Sunpower, 2008; Suntech Power, 2014).

The FU also determines the life cycle stages considered in the system boundary of an ELCA. The system boundary describes the relationship between products or services and the environment and then defines the environmental impacts of each life cycle stage (Heijungs & Guinée, 2012; K. K. Lawania, 2016). In this study, the system boundary has been drawn to include all the processes which were essential in generating electricity from the RAPS systems. The stages include equipment manufacturing, construction, transportation, operation and maintenance, and end-of-life disposal (Figure 3.4 and Figure 3.5). The solid lines in the figure represent the life cycle stages in which material, energy and emissions flow. The dashed lines specify the relationship between the stages. The stage named 'other upstream processes' refers to the additional processes (e.g. road operation and maintenance for the transportation of diesel) that support the major life cycle stages.

Heijungs and Guinée (2012) have identified that some processes included in each life cycle stage might be difficult to quantify. Cut-off criteria for the inclusion of inputs in the life cycle inventory (LCI) were based on mass and energy basis. In this study, the cut-off criteria has been identified based on negligible contribution of the inputs (e.g. paint production, manufacturing of construction equipment) to the total material and energy consumed (Heijungs & Guinée, 2012; Kabir et al., 2012). The next section (3.3.2) identifies all the inputs that were included in the inventory analysis.

3.3.2 Life Cycle Inventory Analysis

Life cycle inventory (LCI) is a prerequisite step in carrying out an impact assessment. A large amount of data is required to build an LCI for the ELCA. This needs information on raw material use, energy consumption and emission releases for each process under each life cycle stage. A mass and energy balance was used to establish the flow of all the inputs and outputs for an ELCA of a defined functional unit (Schofield, 2011). The approach used for the LCI is a "bottom-up method", which collects all relevant information encompassed in the system boundary. All data can be obtained from various sources such as meter readings from actual equipment, industry reports or databases, government documents, interviews, surveys, journals, or reference books (Curran, 2012). Ensuring that the goals of the study are met, the gathering of data could be an iterative process due to the possibility of new data requirements or additional limitations being discovered (ISO, 2006).

In the study, the energy and material inputs were predominantly sourced from Horizon Power for the life cycle inventory. Available information provided by this power distribution utility includes the case study site single line diagrams, power generation equipment technical specifications, RETs and diesel engine operation, power consumption during 2015 and 2016 and their power system planning period. Surrogate data has been sourced from published literature and industry interviews when system specific information was not available from them. This includes material composition and energy use for manufacturing power generation equipment, the mode of transport to bring them to the construction site, the distances travelled between the origin and the construction site, materials and equipment needed for construction and power station maintenance and end-of-life disposal methods. This inventory develops a data bank which is then required in determining the impact assessment results. The establishment of databases on the upstream and downstream processes of the RAPS systems is discussed in detail below.

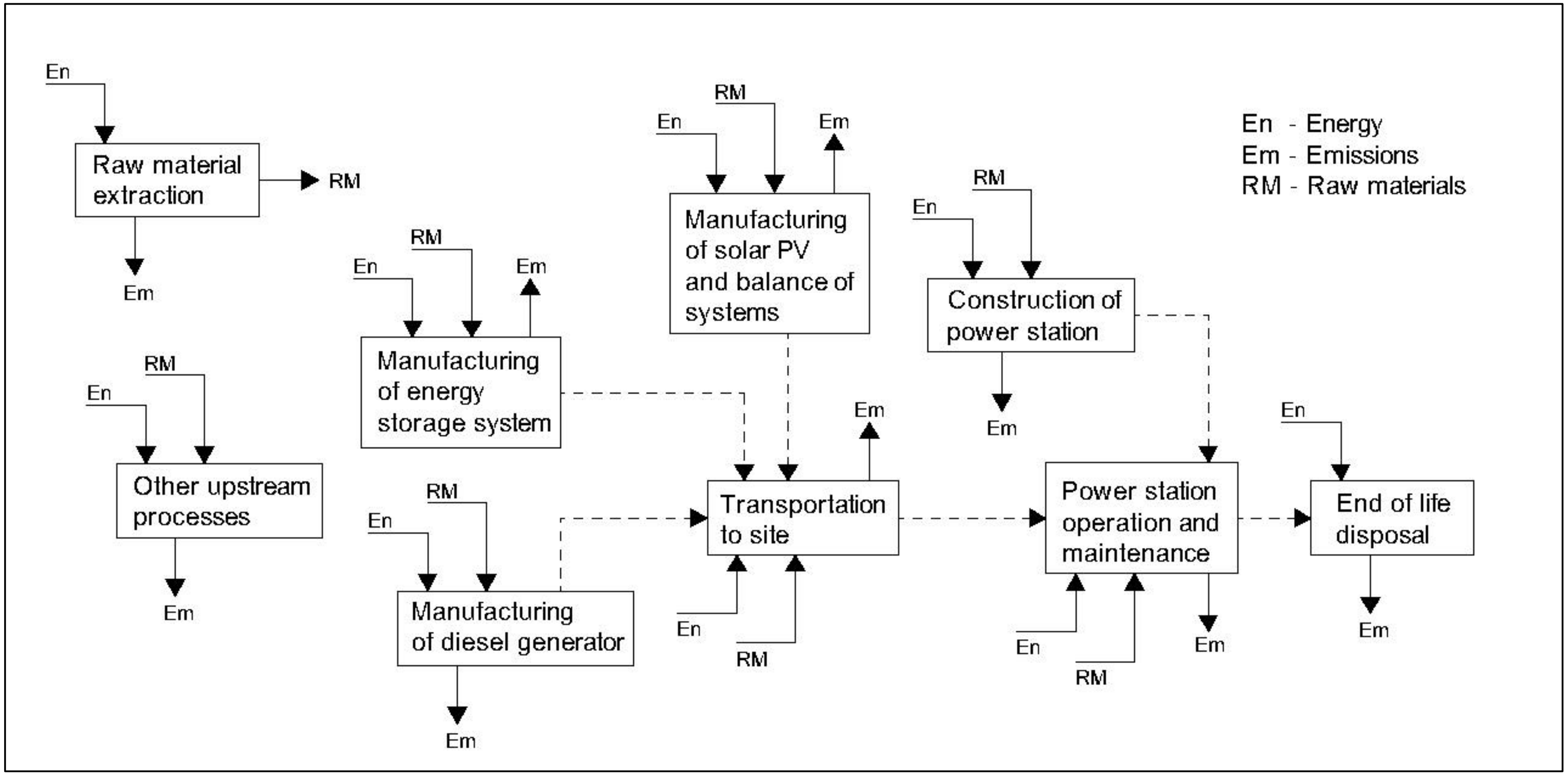


Figure 3.4 Solar PV–diesel hybrid system boundaries for ELCA (Arceo et al., 2017)

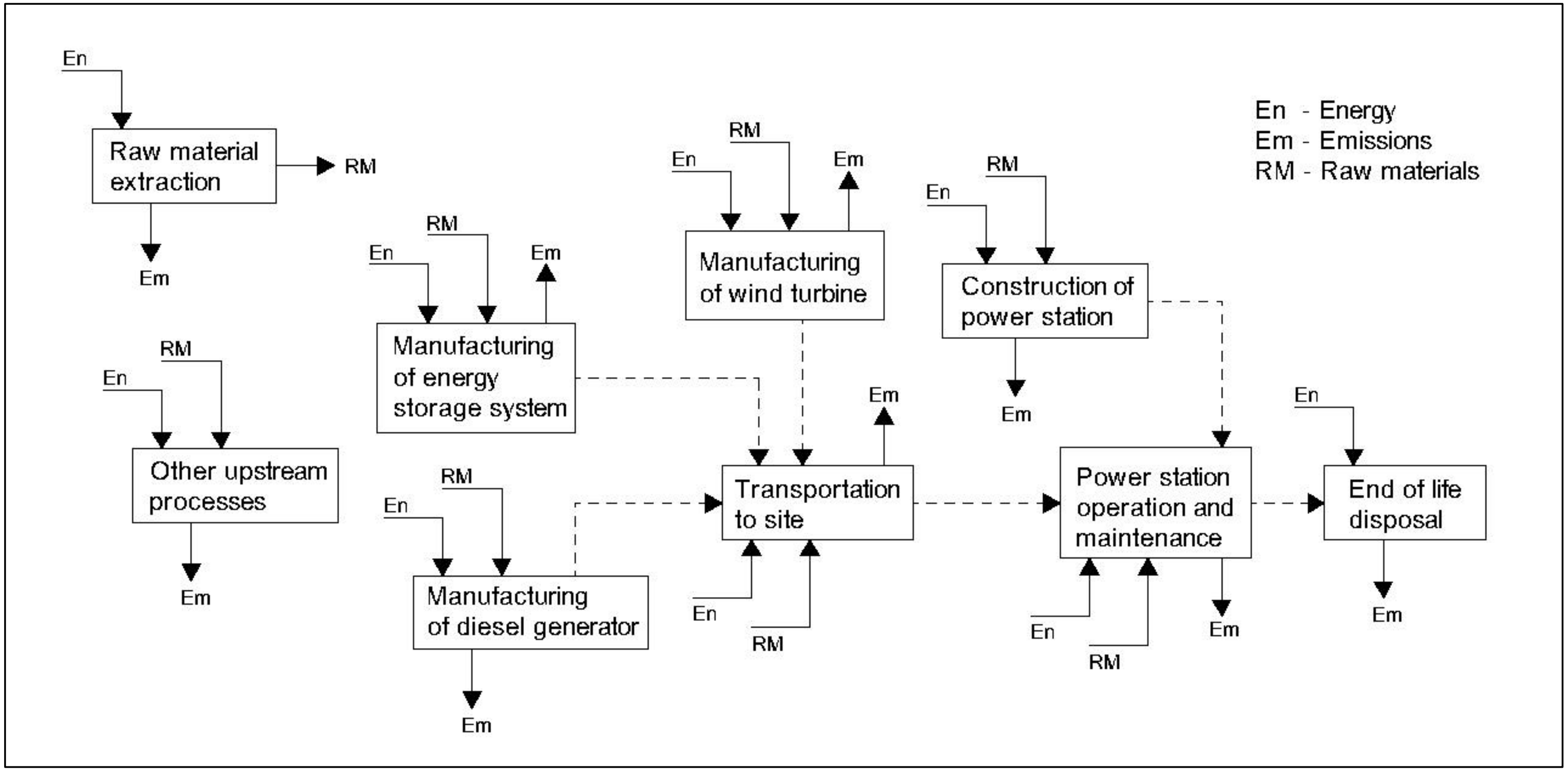


Figure 3.5 Wind-diesel hybrid system boundaries for ELCA (Arceo et al., 2017)

3.3.2.1 *Equipment production*

Mining to material production and manufacturing of equipment have been included in the equipment production stage. These were developed in accordance with the technical specifications of the equipment used for the case study sites. Power generation and energy storage equipment only were considered in the analysis. The following assumptions were considered when developing the system boundary of the equipment production stage.

- Capital infrastructure such as transformers, circuit breakers and other substation equipment has been excluded. The same assumption was also made by other ELCA studies (Chermak, 2009; Schofield, 2011; Smith et al., 2015).
- Power metering devices and residential wiring were not included in this study, as previously done by Smith et al. (2015).
- Power generation equipment was assumed to have low proximity to the control centre, therefore, wirings were excluded in this study (Smith et al., 2015).

Based on the report provided by Horizon Power, the RAPS systems consisted of the following equipment.

- The solar PV-diesel hybrid system in Marble Bar is composed of four 320 kW MTU Detroit diesel engines, 303 kW Sunpower solar PV system and 458 kVA ABB PS04 flywheel grid stabilising generator. The solar PV system includes a 'balance of system' (BOS), which consists of 45 SMA Sunny Boy 7000 HV inverters and 135 T20 Sunpower single-axis trackers.

- The equipment included in the wind-diesel hybrid system in Coral Bay is composed of seven 320 kW MTU Detroit diesel engines, three 275 kW Vergnet GEV MPC wind generators and 458 kVA ABB PS04 flywheel grid stabilising generator.

- The solar PV-diesel hybrid system in Yungngora consists of four 273 kW Scania diesel engines and 175 kW Suntech Power solar PV system. This also includes a BOS comprising of inverters, non-tracking solar PV mount and a battery-inverter solar smoothing energy storage (SSES).

Due to lack of available information, surrogate information on the material composition and manufacturing energy for each equipment was used. A mass and energy balance has been used to estimate the quantities of individual materials and the amount of energy consumed in manufacturing in order to develop the LCI. The material quantities have been estimated with the use of material composition from reliable published sources. The energy for manufacturing the equipment was quantified using the type of energy used, the mass of the equipment and the rate of energy consumption per unit of mass.

3.3.2.2 Construction

The LCIs of equipment transportation were developed through phone interviews and email correspondences to determine the location of the equipment manufacturing site. Since the power generation equipment, BOS and energy storage equipment are manufactured worldwide, an online tool for calculating distances between seaports has been used to estimate the km travelled for transferring the equipment from the respective international port to the closest Australian port. Google Earth software has been used to estimate the approximate distance travelled by trucks to carry the equipment to the construction site. Since the input from transportation is represented by tonnes-km, the mass of the equipment (e.g. PV panels) in tonnes was multiplied by the corresponding distance travelled. The principle of proximity has been followed to transfer the equipment when no specific transport information route was available from manufacturers and retailers (Xu et al., 2017).

The LCIs on the machinery used for construction such as graders, compactors and forklifts including their power rating and time of usage have been obtained from published literature and closest machinery hire companies (TrackLinkWA, A1 Siteworks, Total Forklift Services, Concrete Equipment Suppliers Aust Pty Ltd.) in Western Australia. Additional materials required for construction such as aggregate, concrete and steel have been estimated from the equipment construction manual and manufacturers. The energy consumed to transfer the machineries and the additional construction materials to the construction site have been estimated. Finally, the amount of energy consumed in transporting personnel from the contractor office site to the construction site was not included as this sort of information is not usually recorded.

3.3.2.3 Operation stage: electricity generation

This stage seeks to estimate the amount of material used and emissions released from the electricity generation of the RETs and diesel engines. The solar PV system, wind generators and energy storage systems neither consume materials nor release emissions during electricity generation. Only the emissions from diesel electricity generation have been included in the LCI.

The intra-hour operation of the diesel engines and RETs to generate electricity over the life cycle has been determined using HOMER software. HOMER is an electricity planning and generation modelling software for hybrid renewable and distributed generation systems (HOMER Energy, 2016). This software has been used for simulating the behaviour of the RAPS systems to estimate the diesel engine power production and diesel consumption. This also enables the user to define the distributed generation system configuration by identifying the power rating and number of power generating equipment. In order to simulate RAPS system operation, HOMER requires annual time series load data, solar radiation and wind speed. This simulation includes the determination of available energy from renewable energy sources and then compare this with the current load to possibly store excess energy in the energy storage system (Kyriakidis, 2012). The establishment of HOMER databases such as RAPS system components and site-specific information is discussed in detail below.

Annual load demand

Using the load profile between July 2015 and June 2016 provided by Horizon Power, the annual energy demand in Marble Bar, Coral Bay and Yungngora were estimated as 2,126 MWh, 3,261 MWh and 1,735 MWh, respectively and the daily average demand were 243 kWh, 372 kWh and 198 kWh, respectively. Figure 3.6 shows a box plot of the load profiles of the three sites in average monthly values.

Horizon Power has also provided the load demand forecast of the aforementioned case study sites for the next 20 years. This information indicates that the demand for all the sites will relatively be constant over that period. Therefore, no expansion of capacity has been assumed for the simulation of electricity generation in the subsequent years.

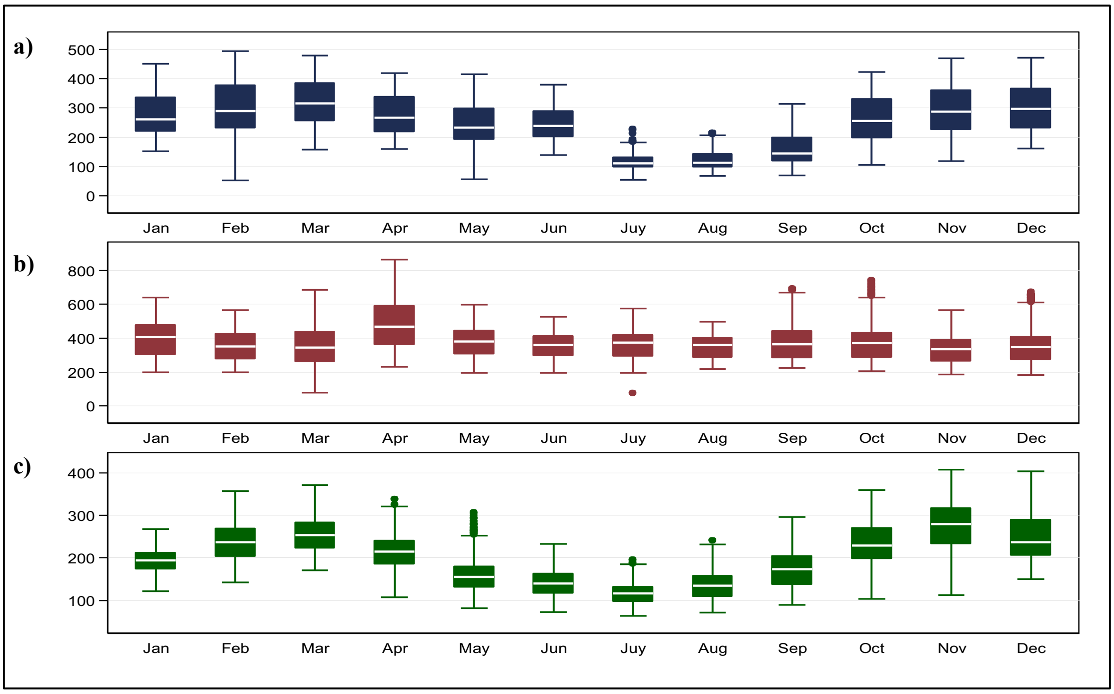


Figure 3.6 Load profile in average monthly values for a) Marble Bar, b) Coral Bay and c) Yungngora (Horizon Power)

Annual solar irradiation

Since inland electricity generation considers the use of solar PV system as a renewable energy resource, monthly solar radiation data has been sourced from the Bureau of Meteorology (BOM). This data has been entered in HOMER software to build a set of 8,760 solar radiation values for each hour of the year. HOMER generates synthesized solar radiation in a data sequence that has a realistic day-to-day and hour-to-hour variability (HOMER Energy, 2016).

The BOM station in Marble Bar has a latitude of -21.78° and a longitude of 119.75°, while the BOM station closest to Yungngora has a latitude of -18.49° and a longitude of 124.40°. Figure 3.7 shows the 2015 solar resource profile for both sites which generates an annual average solar irradiation of 6.09kWh/m^2/day for Marble Bar and 6.21 kWh/m^2/day for Yungngora.

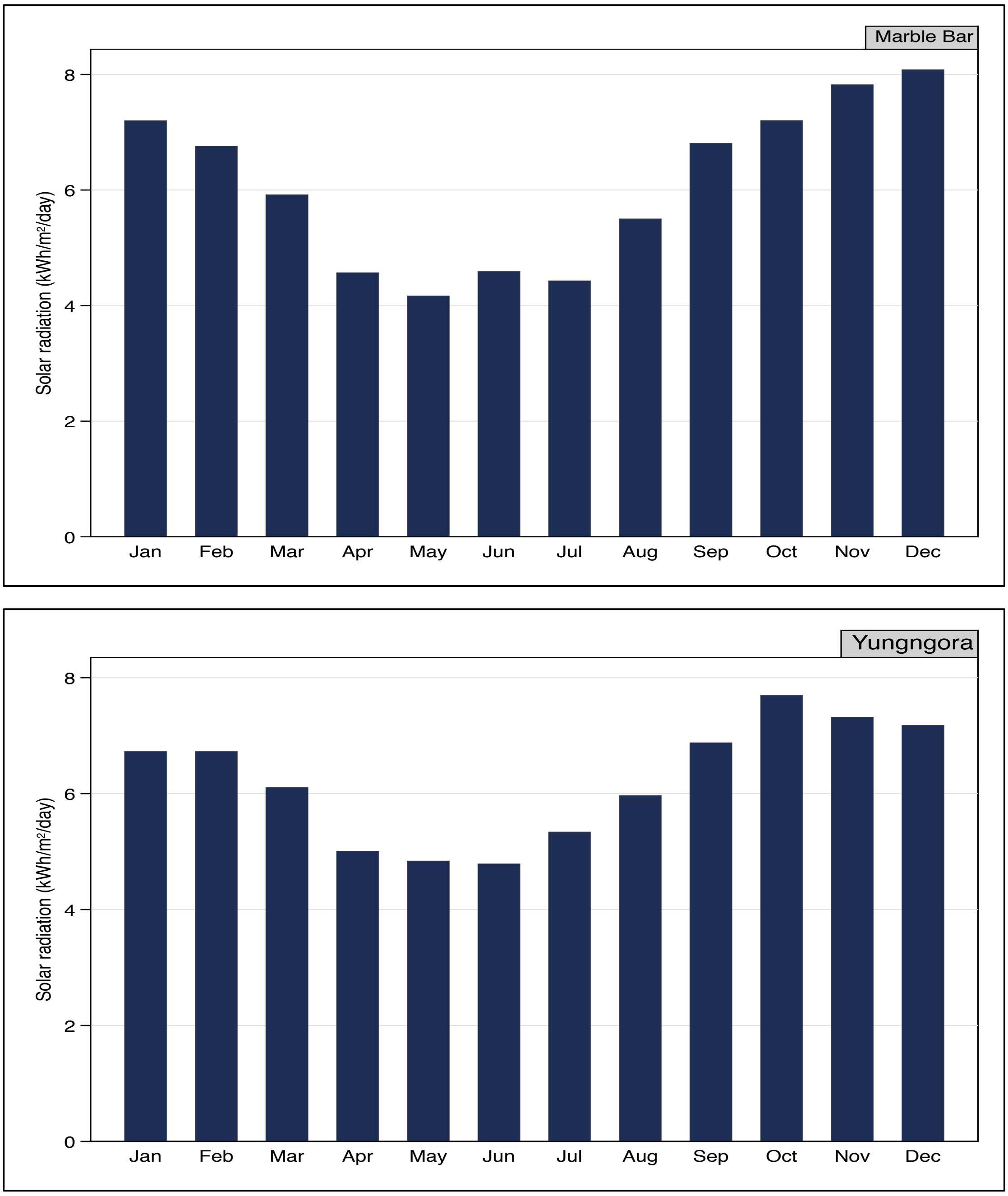


Figure 3.7 Profile of solar irradiation for Marble Bar and Yungngora (BOM, 2017)

Annual wind speed data

Since the utilisation of wind electricity generation is appropriate for coastal regions, the wind speed time series data for the electricity generation in Coral Bay has been sourced from NASA Surface Meteorology available in HOMER software. Figure 3.8 shows the monthly averages of the calculated baseline data expressed in meters per second with an average wind speed of 6.8 m/s. The station where the wind speed time series was generated is located at a latitude of -23.5° and a longitude of 113.5°.

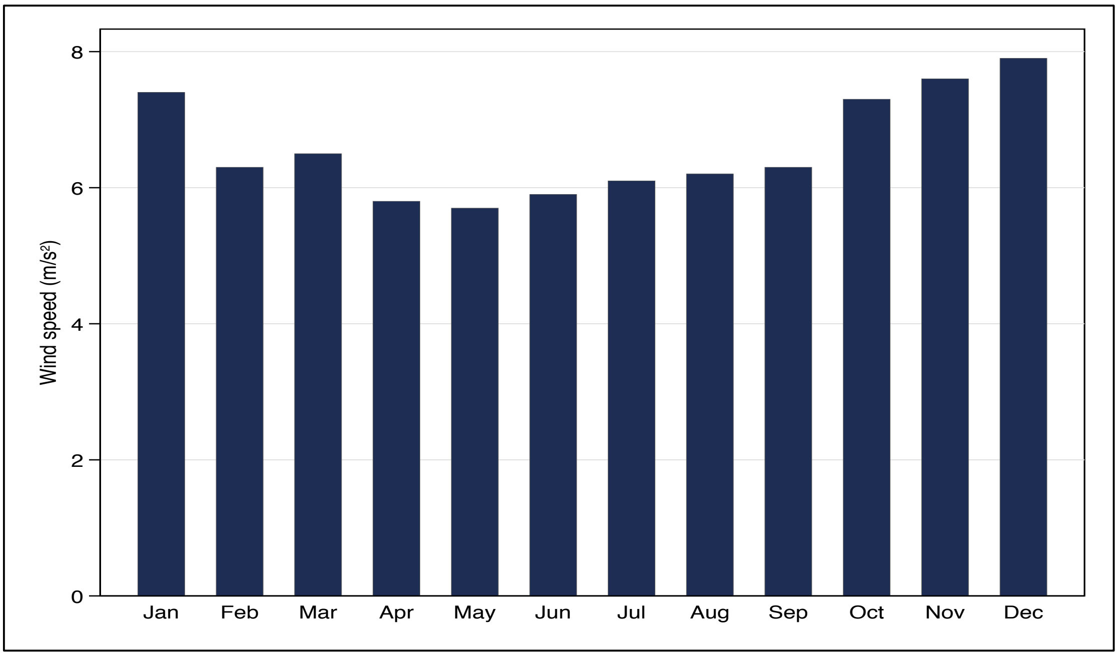


Figure 3.8 Profile of wind speed for Coral Bay (HOMER Energy, 2016)

Diesel engines

Diesel engines are used in the case study sites as an back-up reserve for generating electricity. The lifetime of diesel engines for large-scale electricity production is approximately 8 to 10 years when operated full-load (Schofield, 2011; Smith et al., 2015). However, the lifetime of these engines is expected to increase as the share of electricity generated from diesel engines decreases due to the integration of RETs into the RAPS systems. This study assumed that the diesel engines were not replaced over the life cycle.

The minimum allowable load restriction of the diesel engines affects the permissible penetration of renewable energy generation. Manufacturers often limit the loading level of the diesel engines to 30% of its rated capacity, as operating the engines lower than this value would adversely affect their performance (ARENA, 2014). The effect of this scenario is the deposit build-up of unburned fuel and oil in the piston rings and cylinders, which leads to poor operation efficiency, abrupt breakdown and faster deterioration of parts (Jabeck, 2014). At the point of minimum loading of the diesel engines, the controllers will reduce the power output of RETs to maintain the safe loading level of the diesel engines.

Table 3.1 shows the specific fuel consumptions of both MTU-Detroit and Scania diesel engines that have been extrapolated from actual engine specifications (MTU Onsite Energy, 2016; Scania Industrial & Marine Engines, 2007). These values indicate the amount of diesel consumed by a generator per kWh of electricity generation.

Table 3.1 Specific fuel consumption (L/kWh) of MTU and Scania diesel engines

Generator Loading Level	MTU	Scania
100% load	86.27	70.84
75% load	64.90	54.62
50% load	45.31	38.22

Solar PV panels

The number of solar PV panels used for power supply has been estimated from the type of panels used and the power capacity of the case study sites. The solar PV systems are rated 303.5 kW for Marble Bar and 175 kW for Yungongora. Marble Bar power station uses 1,350 units of 225 kW Sun Power mono-Si solar PV modules with an assumed lifetime of 25 years (Chen et al., 2016). Yungngora power station uses 700 units of 250 kW Suntech Power multi-Si solar PV modules that also has a lifetime of 25 years (Fu et al., 2015; Hong et al., 2016).

HOMER calculates solar power output based on the rated capacity of the panels and incident radiation (HOMER Energy, 2016). SunPower Corporation guarantees a 100% nominal operation of the solar modules at the start of operation with a derating factor of 0.25% every year (SunPower Corporation, 2013). Suntech Power ascertains a nominal power of 97% in the first year of the solar panel operation with 0.7% decrease every year for the next 25 years (Suntech Power, 2014).

Wind generators

HOMER uses libraries of various wind generators from different manufacturers. Three 275 kW_p Vergnet wind generators, which are available in this library are used in Coral Bay. Each wind generator has a hub height of 50 metres and operational lifetime of 20 years. Table 3.2 shows the power curve of this wind generator that has been used to model the wind electricity generation (VERGNET, 2016).

Table 3.2 Power curve of Vergnet wind generators

Wind Speed (m/s)	Power Curve (kW)
2.5	0
3.0	0
3.5	0
4.0	3
4.5	10
5.0	18
5.5	27
6.0	36
6.5	47
7.0	58
7.5	78
8.0	98
8.5	119
9.0	141
9.5	164
10.0	189
10.5	215
11.0	243
11.5	262
12.0	275
Up to 25	275

The determination of the wind farm power output requires the estimation of potential energy losses which can come from the wake effects, wind availability, electrical efficiency, turbine efficiency and environmental losses. On average, the aggregated site-specific total power losses range from 10 to 20 percent (European Wind Energy Association, 2017). Whilst some of these losses may not be relevant for the RAPS system, a 20% energy loss is included in estimating the wind electricity generation in Coral Bay.

Flywheel energy storage

Both Marble Bar and Coral Bay use a PowerStore PS04 flywheel energy storage system from ABB with a minimum lifetime of 20 years. The main components of this equipment include flywheel spinning mass operated by an engine, converter system, operator interface and contained based building (Figure 3.9) (ABB, 2013). According to Vi Garrood of Horizon Power (personal communication), it was known that this equipment acts as a grid stabiliser for the following purposes.

- Inject energy to the distribution system when the solar PV operates below a required level.
- Inject energy to the distribution system when diesel generators are overloaded.
- Store sufficient energy for spinning reserve.
- Provide frequency support to respond to solar power fluctuations.
- Provide voltage support to limit voltage variations.

This energy storage system only acts for ancillary service and does not discharge energy for extended periods of time (Denholm, Ela, Kirby, & Milligan, 2010). The technical specifications of this energy storage system (operating reserve of 458 kW_p and a parasitic load of 12 kW) were available in HOMER library and were used in the simulation of the RAPS system operation.

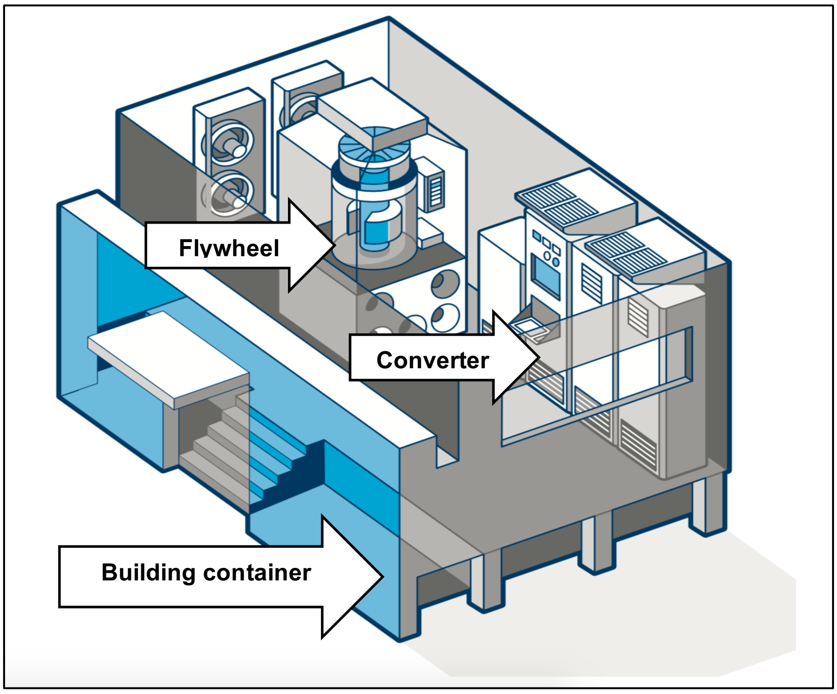


Figure 3.9 Main components of a PowerStore PS04 flywheel energy storage (ABB, 2013)

Batteries

A battery energy storage system consisting of lead-acid batteries is utilised in the hybrid system of Yungngora. According to Vi Garrood of Horizon Power (personal communication), this storage system controls the level of solar PV generation to regulate voltage and frequency variation and stores energy for spinning reserve. Similar to the flywheel energy storage, this battery storage only provides ancillary services and does not discharge energy for long periods of time (Denholm et al., 2010).

Hoppecke 8 OpzV 800 batteries with a lifetime of 20 years are used in the battery energy storage system. Since this brand of battery is not included in HOMER library, a generic variable valve-regulated lead-acid battery of similar voltage and power rating has been used for analysis. Finally, the minimum depth of discharge (DOD) of these batteries was assumed to be 40% following HOMER Energy (2016), as no information on DOD has been found available on Hoppecke battery manuals.

Inverters

Both the solar PV panels and battery energy storage require power electronic inverters to sustain the flow of energy between the DC side and AC side of the RAPS system. The number of inverters used for the case study sites is forty-five 7.5 kW SMA inverters for the Marble Bar solar PV system, ten 13.6 kW KACO Powador inverters for the Yungngora solar PV system and six 30 kW Selectronics inverters for the Yungngora battery storage system. The peak efficiencies of SMA inverters (97.1%) (SMA, 2011), Selectronics inverters (97.2%) (Selectronic, 2016) and KACO Powador inverters (97.8%) (KACO New Energy, 2016) have been included in the analysis, but no degradation limit over the operational life cycle has been assumed. While the lifetime of the inverters ranges from 20 to 30 years according to the manufacturers, a 20-year operational life cycle was assumed conservatively for the study. Therefore, one-time replacement of the inverters has been considered in the analysis over the 25-year operational life cycle of the solar PV-diesel hybrid systems.

Renewable energy penetration

The rate of renewable energy penetration to the hybrid system has also been obtained from HOMER. The maximum amount of renewable energy that can be supplied to the load is calculated using equation 3.1 (HOMER Energy, 2016).

$$p_{max,ren} = \frac{P_{ren}}{L_{served}} \tag{3.1}$$

Where,

$p_{max,ren}$ − maximum renewable energy penetration (%)

P_{ren} − total renewable energy output from solar PV or wind generator (kW)

L_{served} − total electrical load supplied (kW)

The fraction of actual renewable energy delivered to the load is calculated using equation 3.2 (HOMER Energy, 2016).

$$p_{ren} = 1 - \frac{P_{nonren}}{L_{served}} \tag{3.2}$$

Where,

p_{ren} − renewable energy penetration (%)

P_{nonren} − total nonrenewable energy output (kW)

Renewable energy is not fully utilised to supply the load in a hybrid system. The technical constraints that hinder the maximum penetration of RETs through a renewable and diesel hybrid system are as follows.

- Firstly, the operation of RETs often produces surplus electricity during times of high wind or solar irradiation (HOMER Energy, 2016). This energy could end up being excess electricity unless stored in a battery bank or absorbed by dump loads.
- According to Horizon Power, if the diesel engines are approaching their minimum allowable loading (30% of rated capacity), the plant controller transmits a signal to the RETs to reduce their power output to maintain this minimum diesel engine load. During these instances, the potential energy generated from renewable sources is not fully used to supply the required load.

3.3.2.4 Operation stage: fuel transportation

The information on fuel transportation has been obtained by interviewing Horizon Power, BP Australia and diesel retailers including Recharge Petroleum and Refuels Australia. This information includes the mode of diesel transport that is via ship tanker and truck.

Google Earth and the online seaport distance calculating tool have been used to estimate the distances from refineries to ports and ports to power generation site. The amount of diesel transported was estimated in HOMER software. The input from fuel transportation in tonnes-km is calculated by multiplying the mass of diesel in tonnes by the length of distance travelled to transport this fuel to the power generating site.

3.3.2.5 Maintenance stage

The inventory of the maintenance stage includes energy and material inputs in retaining the prime operating conditions of the power generation equipment. The maintenance stage involves three major activities including the use of consumables (water for cleaning the solar panels), personnel transport to the power station for overhauling and preventive maintenance purposes, and the replacement of BOS including batteries and inverters for the solar PV-diesel hybrid system and gearbox for the wind-diesel hybrid system. Since the information on these maintenance activities was proprietary, power generation equipment manuals and publicly available literature were reviewed to gather relevant information (Hyundai; MTU Friedrichshafen GmbH, 2003, 2012; Perkins Engines Company Limited, 2008; Scania Industrial & Marine Engines, 2007) (ABCSE; Clark, 2014; CO2CRC et al., 2015; Demir & Taşkın, 2013; Eco Cleaning System; Guezuraga et al., 2012; Haney & Burstein, 2013; Hou et al., 2016; Hyundai; IREC, 2010; Kabir et al., 2012; Kannan et al., 2006; Morton, 2012; NREL, 2015).

The inventory analysis of the maintenance stage has a number of data limitations that may underestimate the evaluation of environmental impacts.

- The energy consumption from the use of tools for preventive maintenance and overhauling was not included as this information is not usually recorded.
- Lubricant oil and paint for maintenance of the wind generators were not included as these only represent 1% of the overall material (Xu et al., 2017) and have negligible environmental impact (Guezuraga et al., 2012; Kabir et al., 2012; Uddin & Kumar, 2014).

3.3.2.6 End-of-life disposal stage

There is a little information on recycling and remanufacturing of diesel engines, solar PV panels, wind generators and batteries in Australia. Therefore, only the disposal of these components to landfill was considered as the end-of-life. This study assumed that 100% of the materials of each component has been disposed to landfill. Similar studies on ELCA of solar PVs, wind generators and diesel engines have found that the disposal of these components to landfill contribute significant environmental impacts (Benton et al., 2017; Guezuraga et al., 2012; Kabir et al., 2012; Zhong et al., 2011).

3.3.3 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) aims to evaluate the environmental impacts over the life cycle of products or services (Heijungs & Guinée, 2012). This step includes the selection of impact categories and characterisation models, characterisation of these impacts (conversion of the LCI database to impact category units for estimating the environmental impact results), normalisation of characterised values (conversion of all impact categories into a common unit to compare the relative magnitude of all environmental impact results) and weighting of normalised values (aggregation of the environmental impact results using a weighed equivalence factor) (Bekkelund, 2013; Fu et al., 2015; Schofield, 2011).

The environmental impacts that have been selected for the impact assessment are shown in Table 3.3. Whilst the Australian indicator set from SimaPro 8.2.3 software cannot calculate all these impacts, a review of international and Australian best practices (Bare, 2012; Bengtsson & Howard, 2010a; Biswas, Alhorr, Lawania, Sarker, & Elsarrag, 2017; Goedkoop et al., 2009; Humbert, Schryver, Bengoa, Margni, & Jolliet, 2012; Renouf et al., 2015) has been performed to select characterisation models that are applicable and relevant for Australia. From this review, relevant characterisation methods available from SimaPro 8.2.3 were used for estimating the environmental impacts (Table 3.3).

The energy and material inputs from the LCI have been entered into SimaPro software (PRé-Consultants, 2015) by linking these inputs (e.g. α m^3 of diesel per kWh of electricity generation) to relevant emission databases (e.g. γ kg CO_2 eq per m^3 of diesel production) in order to calculate emissions (e.g. $\alpha\gamma$ kg CO_2 per kWh of electricity generation). It was endeavoured to choose local emission databases as much as possible to represent the local situation. Emission databases on libraries included in the SimaPro software contain emission factors from overseas (Ecoinvent 3) and Australian (AusLCI Unit Processes) material, energy, transportation and waste inputs. Ecoinvent 3 has only been used to estimate the impacts from mining to the manufacturing of power generating equipment since all of the components were manufactured outside of Australia. The appropriate use of databases not only represent the regionalised effect of emission factors in the area of study but also improve the reliability of the results (Chen et al., 2016).

Table 3.3 Characterisation models for estimating the impact categories

Characterisation Model	Impact Category	Unit
IPCC GWP 100	Global warming	tonnes CO_2 eq
Australian indicator set v2.01	Eutrophication	kg PO_4 eq
	Land use and ecological diversity	Ha a
	Water depletion	m^3 H_2O
CML 2 baseline 2001	Fossil fuel depletion	MJ
	Mineral depletion	kg Sb eq
	Acidification	kg SO_2 eq
	Ozone depletion	kg CFC-11 eq
ReCiPe 2008	Freshwater ecotoxicity	kg 1,4-DB eq
	Marine ecotoxicity	kg 1,4-DB eq
	Terrestrial ecotoxicity	kg 1,4-DB eq
	Human ecotoxicity	kg 1,4-DB eq
	Ionising radiation	kg U235 eq
	Photochemical smog	kg NMVOC
TRACI v2.1	Respiratory inorganics	kg $PM_{2.5}$ eq

CO_2 – carbon dioxide, PO_4 – phosphate, Ha. a – hectare years, Sb – antimony, SO_2 – sulphur dioxide, CFC – cholorofluorocarbon, U235 – uranium 235, NMVOC – non-methane volatile organic compounds, PM – particulate matter, eq - equivalent

The SimaPro software would classify and aggregate these emissions into environmental impacts. The resulting values for all impacts are represented in their respective impact category units. While fossil fuel depletion is given in units of 'MJ', the estimated value has been converted to units of 'kg Sb eq'. The equivalent fossil fuel depletion for the use of 1 MJ of fossil fuel is equivalent to 4.81×10^{-4} kg Sb eq Oers, Koning, Guinee, and Huppes (2002). The characterised results represent the impacts associated with the mining to the manufacturing of the power generation equipment, equipment transportation, construction, power generation, fuel transportation, maintenance and end-of-life disposal of the RAPS systems.

In this study, the characterised values of the impacts have been normalised using normalisation factors in order to compare the environmental impacts at the same unit level (e.g. equivalent inhabitants) and to help in determining the most detrimental impact that requires immediate priority for mitigation (Fu et al., 2015). The reference region is an important factor in normalising characterised environmental impact values (Chen et al., 2016; Zhong et al., 2011). Specific Western Australian regional normalised factors (e.g. Mid-West, Gascoyne, Kimberley) would provide a more accurate result. However, there are no studies conducted that document this information. Foley and Lant (2009) generated normalisation factors for 9 environmental impacts, but this present study characterised 15 impacts. The lack of available and complete normalisation data for the regional areas in Western Australia leads to the use of the Australian normalisation factors by Bengtsson & Howard (2010b). Whilst using these normalisation factors does not represent region specific impacts of the RAPS systems, the completeness of the normalisation values can assist in the comparison of all the environmental impacts at the same unit level and reference location. The use of a non-region specific normalisation factor may cause inaccuracy in the selection of the significant environmental impacts and this is considered as an important limitation of the study.

3.3.4 Life Cycle Interpretation

Life cycle interpretation is the final step of ELCA, which evaluates both the life cycle inventory and life cycle impact assessment with respect to the goal and scope of the study (ISO, 2006). This specifically assesses the appropriateness of the functional unit and system boundary, identifies the limitations due to data quality, evaluates the comprehensiveness and sensitivity of the results and interprets the outcomes of the ELCA to arrive with conclusions and recommendations (Heijungs & Guinée, 2012).

This step identifies the hotspots, which are the processes and inputs (e.g. chemicals and energy) in the life cycle of products or services that contribute the greatest share in each environmental impact. The main cause of these hotspots can be identified with the aid of a process network in SimaPro software (Figure 3.10) to determine the breakdown of the environmental impacts.

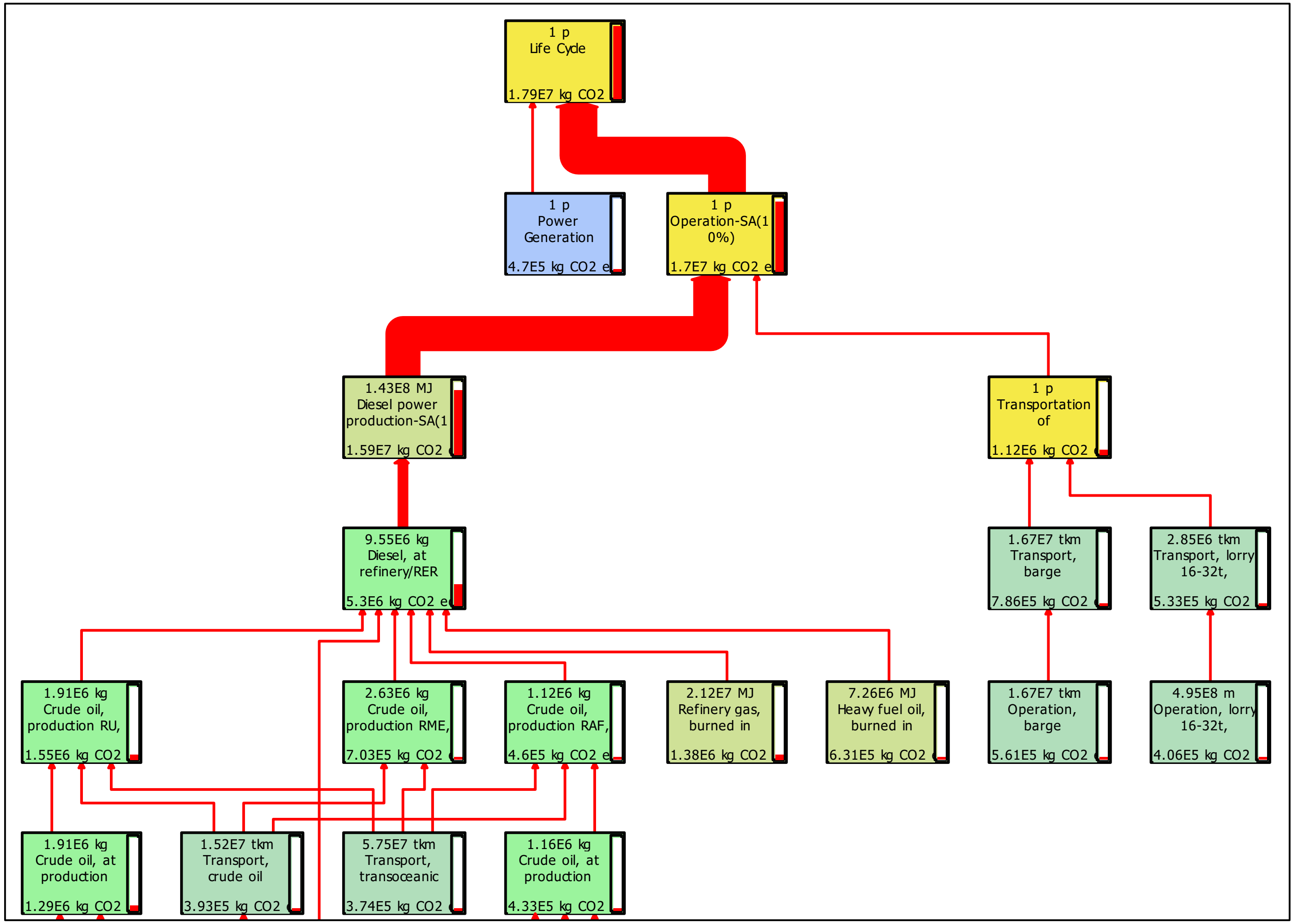


Figure 3.10 Sample process network of global warming potential (kg CO_2 eq) generated by a Simapro LCA software (Source: PRé-Consultants, 2015))

Whilst different products have different contributions to environmental impacts, this step of ELCA can also identify the reasons why the impacts of some processes and inputs are predominant. This establishes a sound explanation on the cause of the findings and provides a basis for further investigation of ways to possibly reduce each environmental impact (Bekkelund, 2013; Schofield, 2011).

The characterised values of 15 environmental impacts have been investigated individually to identify hotspots and then compared with published literature. The identification and implementation of eco-efficiency strategies have been applied to the identified hotspots to further reduce the environmental impacts.

3.4 Step 2: Identification of Eco-Efficiency Strategies

Application of eco-efficiency strategies has been included in the EEA framework to treat the identified environmental hotspots of the RAPS systems. Eco-efficiency involves a continuous application of resource efficient strategies to develop financial profitability, operational efficiency and business productivity in a business process (Kazmierczyk, 2002; van Berkel, 2007). The definition of eco-efficiency by the World Business Council for Sustainable Development imparts that businesses would achieve economic progress with the efficient utilisation of resources and reduction of wastes (van Berkel, 2007; Verfaillie & Bidwell, 2000). This suggests that the use of fewer inputs in any products or services is far more important than limiting its own production. The seven eco-efficiency strategies are listed below (van Berkel, 2007; Verfaillie & Bidwell, 2000).

- Reduction of material intensity (e.g. improving diesel engine load restriction)
- Reduction of energy intensity (e.g. integrating exhaust gas recirculation)
- Reduction of the dispersion of toxic substances (e.g. use of less toxic diesel engine coolant)
- Enhancement of recyclability of materials
- Maximise sustainable use of renewable resources (e.g. maximisation of installed renewable energy capacity)
- Extend product durability (e.g. hybridising diesel engines with RETs)
- Increase the service intensity of products or services (e.g. hybridising diesel engines with RETs)

One or a combination of these eco-efficiency strategies can be considered to treat the environmental hotspots. For remote area power supply, eco-efficiency is applied to ensure a reliable, high-quality and low emission intensive power supply (ARENA, 2014). This can be achieved with the use of enabling technologies such as RETs and energy efficient technologies, which increase the penetration of renewable energy (ARENA, 2014). Eco-efficiency strategies have been selected and applied to the environmental hotspots in the RAPS systems (Figure 3.11).

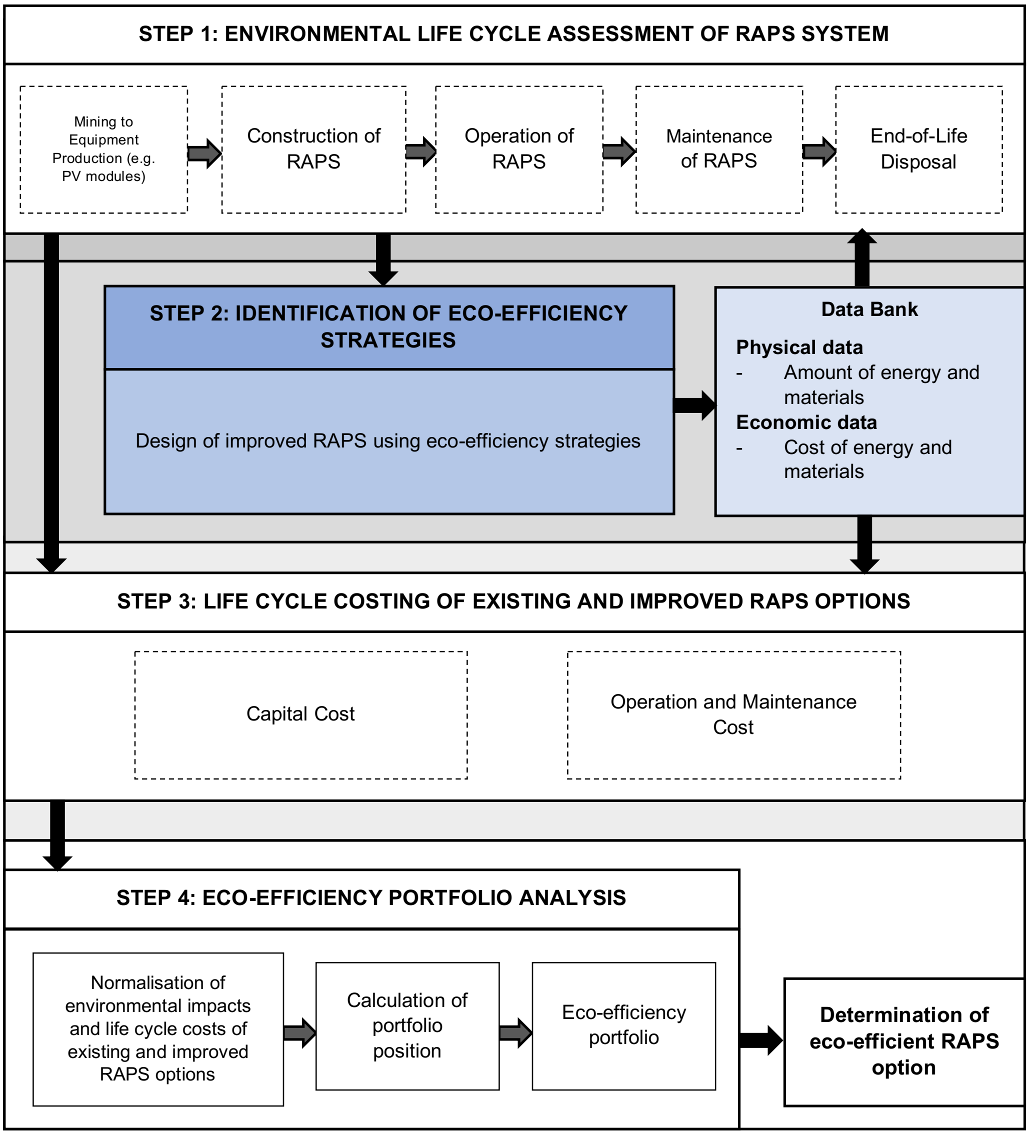


Figure 3.11 Development of improved RAPS options using eco-efficiency strategies

Follow up ELCAs have been conducted for each of the improved RAPS option since the incorporation of a strategy would change the LCI of the RAPS system to some extent. The goal of this new ELCA is to compare the environmental performance of the existing RAPS with the improved RAPS option. The current LCIs in the data bank have been updated once an eco-efficiency strategy has been incorporated into the ELCA. These revised LCIs were then entered into SimaPro software to estimate the environmental impacts. The estimated environmental impacts have been compared with those of the existing RAPS system to estimate the potential environmental improvement. Once environmental saving potentials are ascertained, it is important to understand any economic implications.

3.5 Step 3: LCC of Existing and Improved RAPS Options

Both existing and improved RAPS options have been assessed for determining cost-effective options. The economic feasibility of improved RAPS options is also a relevant criteria for the sustainability of power supply in remote areas (ARENA, 2014; Evans & Peck, 2011). LCC is an accepted economic tool to assist energy planners in comprehensive decision making (Abbes et al., 2014; Fan, 2014). Figure 3.12 shows that LCC was used as a tool to evaluate the economic performance of the improved RAPS options.

The LCC was conducted following the guidelines in AS/NZS 4536:1000 Australian/New Zealand Standard Life cycle costing application guide (Standards Australia/Standards New Zealand, 2014). This LCC standard is used in Australia by project developers and government institutions such as the New South Wales Treasury (2004) and the Australian National Audit Office (2011). The AS/NZS 4536:1000 is used with ISO 14040-44 Life Cycle Assessment guidelines as a parallel methodology for assessing the economic performance of products or services (Ally & Pryor, 2016). In performing a complimentary assessment of the two methods, benchmarking LCC within the same functional unit and system boundaries as ELCA helps maintain a consistent comparative analysis (Kicherer et al., 2007; K. K. Lawania, 2016; Vlachý, 2014) (Figure 3.12).

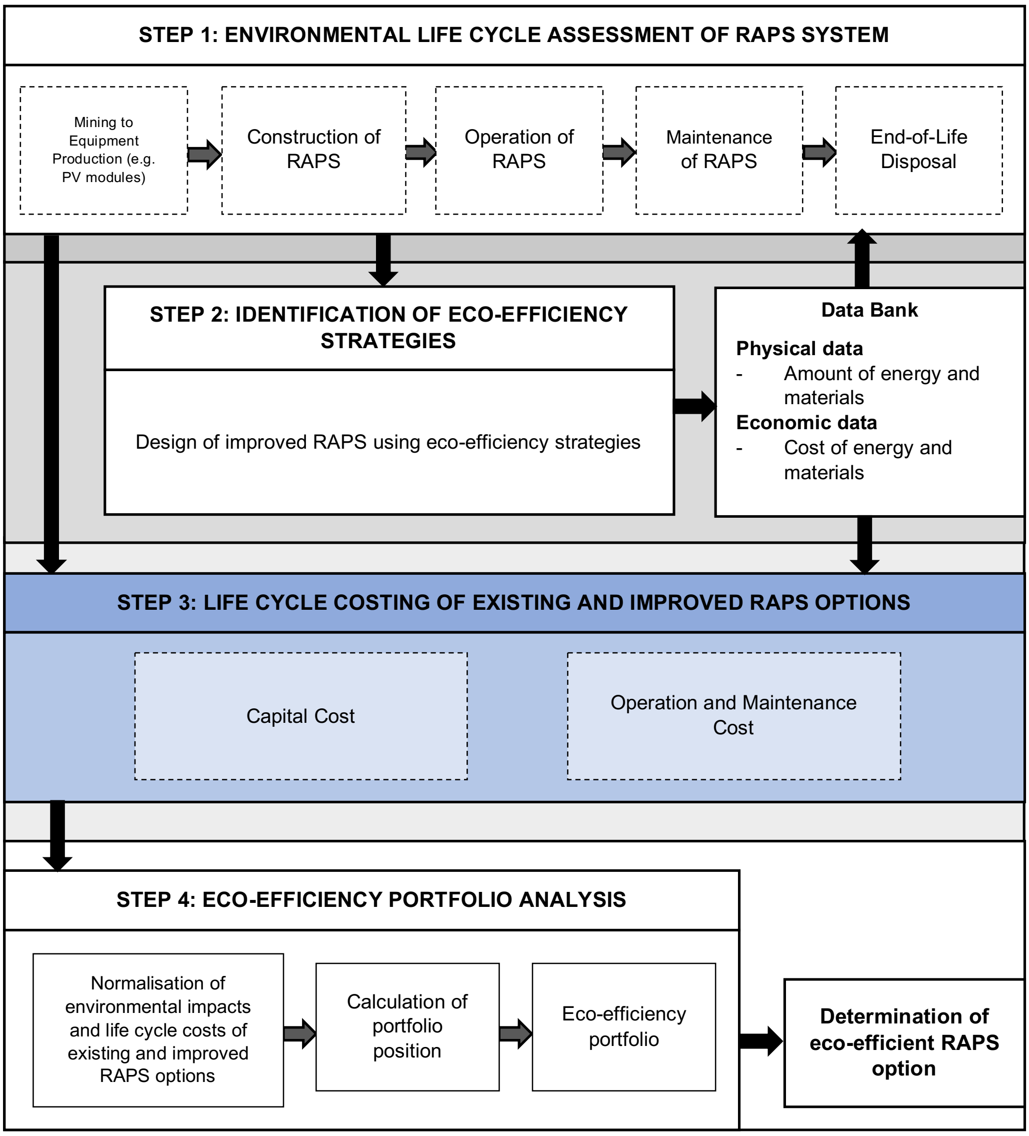


Figure 3.12 Life cycle costing part of the EEA framework

The FU used for the LCC is 1 MWh of electricity generation. This covers the capital and operation and maintenance of a RAPS system with an operational life of 25 years for the solar PV-diesel hybrid system and 20 years for the wind-diesel hybrid system. Exactly the same inputs that were used in the LCIs of the ELCA were considered in this LCC analysis wherein the energy and material values (e.g. MJ, kg) were replaced with dollar values. The study has few limitations due to the following considerations.

– The concept and definition phase including market study, regulatory factors and project management, as well as support services such as corporate management, administrative overheads, insurances and taxes have been excluded from the LCC.

– Dismantling and disposal costs of the power generating equipment have not been included in the analysis due to lack of authentic information.

An extensive cost estimation model using a bottom-up approach has been used to estimate all the cost element values. Although the bottom-up approach makes the LCC data intensive, this ascertains the individual identification and estimation of each cost element (Vlachý, 2014). Cost data has been sourced from relevant Western Australian equipment manufacturers and energy operators whenever possible to develop a life cycle inventory for estimating the costs. In cases when site-specific cost data is not available but is needed by the model, engineering analysis was used to estimate reasonable cost figures. This cost inventory was also incorporated into the databank, which aids in the evaluation of the life cycle costs of the existing and improved RAPS options.

Effort was made to use real costs to remove the uncertainty associated with technology and service inflations. This cost also determines the full cost implications of the existing and improved RAPS options over the entire life cycle. All life cycle costs have been discounted to 2017 values in which the eco-efficiency strategies were implemented. These discounted real costs consider the time value of money which extends over the power supply system life cycle. A real discount rate of 9% was used to calculate the present value, as the same rate was applied by Australian studies in discounting the cost of power generating technologies (BREE, 2012, 2013; CO2CRC et al., 2015). In Australia, a maximum real discount rate of 9% was also applied by companies in calculating the required rate of return of investment (Standards Australia/Standards New Zealand, 2014).

The overall life cycle costs have been estimated by aggregating the individual NPV of each cost element, which results in a single dollar value (Equation 3.3).

$$\mathrm{LCC_{RAPS}} = \mathrm{NPV_{capital}} + \mathrm{NPV_{O\&M}} \tag{3.3}$$

Where,

LCC_{RAPS} – life cycle cost for the capital and operation and maintenance of existing and improved RAPS options (AUD)

$NPV_{capital}$ – NPV of the upstream stages (AUD)

$NPV_{O\&M}$ − NPV of the downstream stages (AUD)

The LCC results for each improved RAPS option were compared with the LCC of the existing RAPS system to assess their economic viability. It must be noted that some options may not be cost-effective but environmentally friendly since the integration of a technology to improve a system's environmental performance may require additional costs (Arceo et al., 2017). This makes it difficult for energy planners to make an option selection. Regardless whether the improved RAPS options were cost-competitive or not, the eco-efficiency portfolio analysis of the options can thus be incorporated to facilitate the decision making process by selecting eco-efficient RAPS options.

3.6 Step 4: Eco-Efficiency Portfolio Analysis

As part of this MPhil research, Arceo et al. (2017) demonstrated that this EEA framework can potentially help to determine eco-efficient RAPS options (Appendix A). This paper identified that the eco-efficiency concept can assist in determining ways to reduce life cycle environmental impacts of RAPS systems in a cost-competitive manner. In order to illustrate eco-efficiency amongst options, an eco-efficiency portfolio, a two-dimensional diagram was developed for comparative analysis (Figure 3.13). The y-axis represents the normalised environmental impacts, wherein an option with the lowest environmental impact value lies above the portfolio. The x-axis represents the normalised costs, wherein an option with the lowest cost value is situated farther to the right of the portfolio. Eco-efficient options are located on and above the diagonal line or the eco-efficiency line (area shaded in green). The most eco-efficient RAPS option has the largest perpendicular distance above the eco-efficiency line. Less favourable RAPS options are located below the eco-efficiency line (area shaded in red), where high environmental impact and life cycle cost exist.

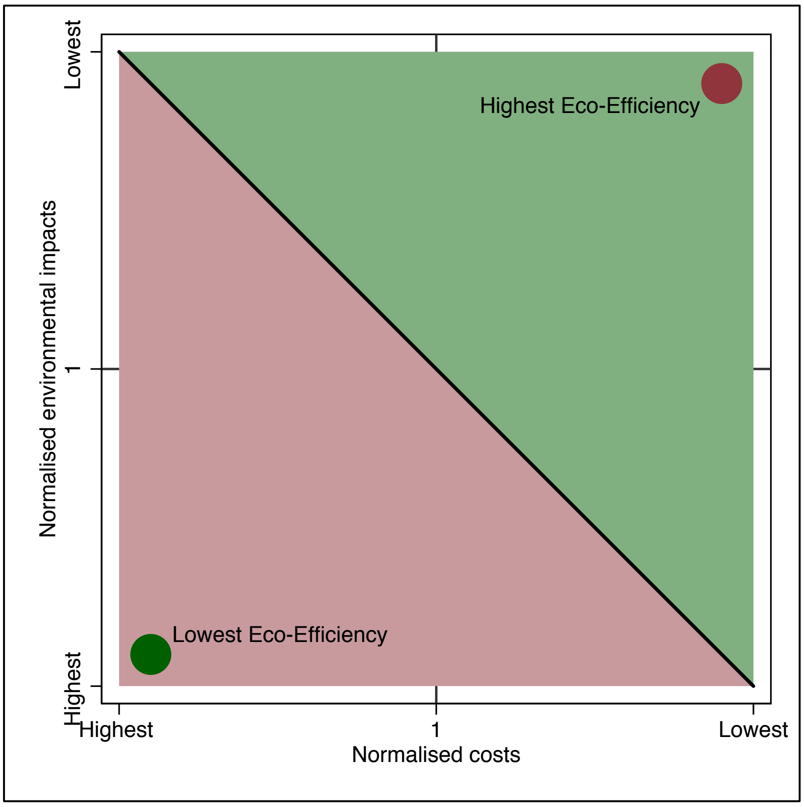


Figure 3.13 Eco-efficiency portfolio of the EEA framework (Source: Personal collection)

The results of the ELCA and LCC analyses were used to generate the eco-efficiency portfolios. Shonnard et al. (2003) described that an option that is not economically viable can be considered eco-efficient if it has better environmental performance. Therefore, the determination of eco-efficiency portfolio is important as this synergizes the trade-off between environmental impacts and costs (Kicherer et al., 2007; Saling et al., 2002). With the aim of implementing appropriate eco-efficient RAPS options, portfolio analysis of the existing and improved RAPS options were conducted for the comparison of their eco-efficiency performance (Figure 3.14). The steps for determining the eco-efficiency portfolios are as follows.

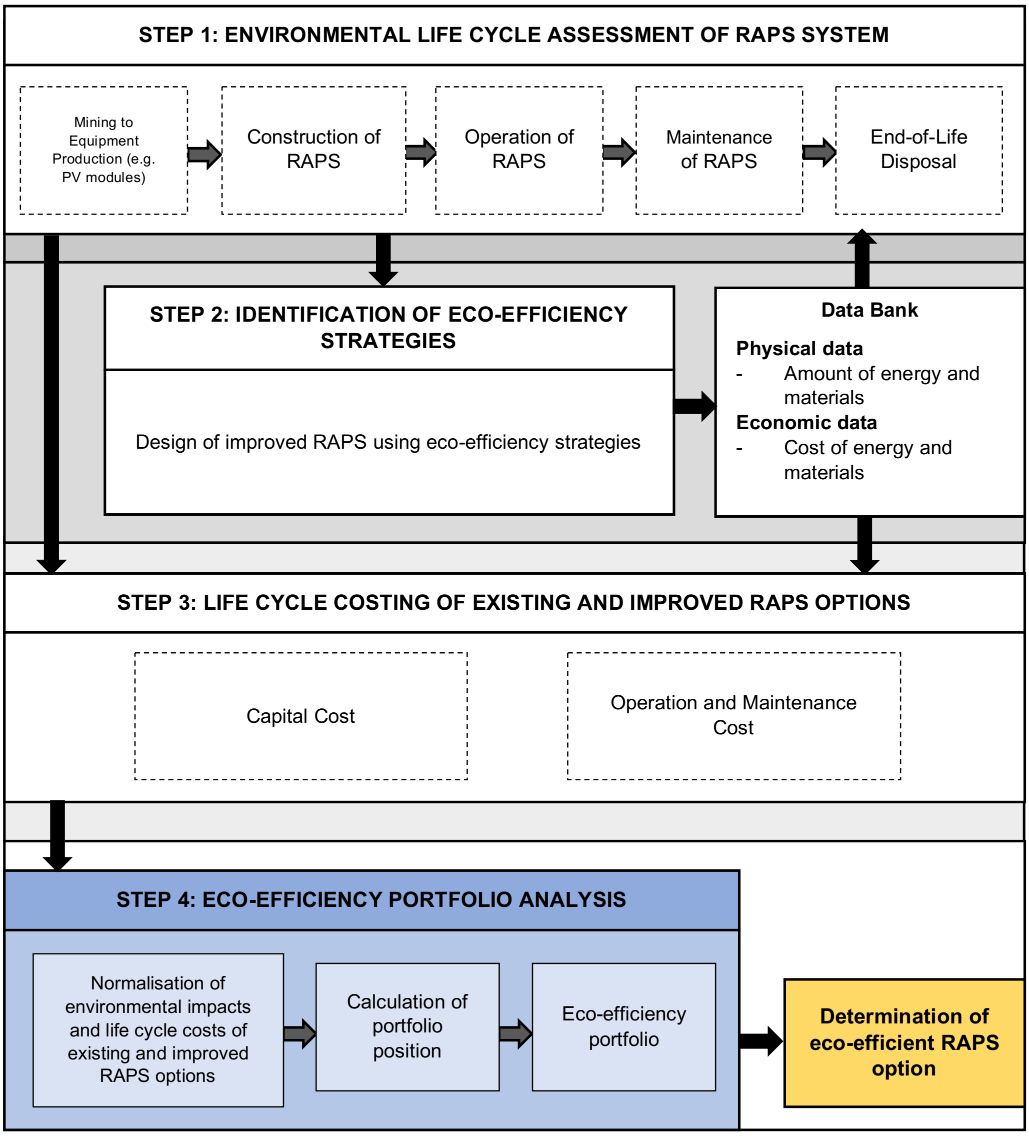


Figure 3.14 Eco-efficiency analysis of existing and improved RAPS options

3.6.1 Normalisation of the environmental impacts

A single metric representing all environmental impacts in the life cycle of a RAPS system was calculated using normalisation and weighting factors. This was done by normalising the fifteen impact categories, followed by weighting them according to an equivalence factor that represents their relative importance and then aggregating the results. The steps for calculating the normalized environmental impacts were as follows.

– The characterised life cycle environmental impacts have been normalised using the latest Australian gross domestic environmental impacts (GDEIs) (Bengtsson & Howard, 2010b). The individual GDEIs are in units of the midpoint categories per number of Australian inhabitants per year, which represent the equivalent amount of impact an individual inhabitant releases (Table 3.4). The normalised value of each environmental impact is then calculated using equation 3.4.

$$NV_i = \frac{LCEI_i}{GDEI_i} \text{ [Inh]} \tag{3.4}$$

Where,

NV − normalised value of each environmental impact

$LCEI$ – life cycle environmental impact during mining to the manufacturing of power generation equipment, construction, operation and maintenance and disposal

$GDEI$ – gross domestic environmental impact

i – $1, 2 \cdots 15$ (global warming potential, mineral depletion, fossil fuel depletion, land use and ecological diversity, water depletion, eutrophication, acidification, freshwater ecotoxicity, marine ecotoxocity, terrestrial ecotoxicity, photochemical smog, ozone depletion, ionising radiation, human toxicity and respiratory inorganics)

- The normalised values of the 15 environmental impacts have been aggregated into a single value by considering the relative importance of each indicator in Australia. Weighting factors represent the magnitude of importance of each environmental impacts for Australian conditions (Howard, Bengtsson, & Kneppers, 2009) (Table 3.4). The normalised environmental impacts were calculated using equation 3.5.

$$EI = \sum_{i=1}^{15} NEI_i \times WF_i \text{ [Inh]} \tag{3.5}$$

Where,

EI – normalised environmental impacts in ‘equivalent inhabitants’

WF − weighting factor ($\sum WF_i = 100\%$)

Table 3.4 Normalisation and weighting factors for conducting the impact assessment (Bengtsson & Howard, 2010b; Howard et al., 2009)

Impact Categories	Gross Domestic Environmental Impact (per inhabitant per year)	Weighting Factor
Global warming potential	28,690 tonnes CO_2 eq	19.5%
Fossil fuel depletion	298.55 kg Sb eq	4.1%
Mineral depletion	1.45 kg Sb eq	4.1%
Land use and ecological diversity	26 Ha a	20.9%
Water depletion	930 m^3 H_2O	6.2%
Eutrophication	19 kg PO_4 eq	2.9%
Acidification	123 kg SO_2 eq	3.1%
Freshwater ecotoxicity	172 kg 1,4-DB eq	6.9%
Marine ecotoxicity	12,117,106 kg 1,4-DB eq	7.7%
Terrestrial ecotoxicity	88 kg 1,4-DB eq	10.3%
Photochemical smog	75 kg NMVOC	2.8%
Ozone depletion	0.002 kg CFC-11 eq	3.9%
Ionising radiation	1,306 kg U235 eq	1.9%
Human toxicity	3,216 kg 1,4-DB eq	2.7%
Respiratory inorganics	45 kg $PM_{2.5}$ eq	3.0%

3.6.2 Normalisation of the costs

The life cycle costs of the existing and improved RAPS options were normalised using the latest Australian gross domestic product (GDP) to represent the costs equivalent to the number of inhabitants producing the same amount of GDP per year (Equation 3.6) (Kicherer et al., 2007).

$$\mathrm{NC} = \frac{\mathrm{LCC_{hybrid}}}{\mathrm{GDP}}\ [\mathrm{Inh}] \qquad (3.6)$$

Where,

NC − normalised cost impacts in 'equivalent inhabitants'

3.6.3 Calculation of eco-efficiency portfolio positions

The subsequent steps have been followed to calculate the portfolio positions in illustrating the relative eco-efficiency among options.

– The relation of the normalised environmental impact and normalised cost axes of the eco-efficiency portfolio has been quantified to determine which pillar of sustainability is more influential in the selection of an eco-efficient option (Equation 3.7) (Kicherer et al., 2007; Saling, 2016).

$$R_{e,c} = \frac{(\sum EI)/j}{(\sum NC)/j} \tag{3.7}$$

Where,

$R_{e,c} -$ environment to cost relevance factor

$j -$ number of the existing and improved RAPS options

A relevance factor greater than 1 suggest that the normalised environmental impact of all the options has greater significance than the normalised cost and vice versa.

– Preliminary portfolio position of each improved RAPS option has been calculated by dividing the normalized impact/cost by the average normalised impact/cost value (Equation 3.8 and 3.9) (Kicherer et al., 2007).

$$PP_{e,n} = \frac{EI_n}{(EI)/j} \tag{3.8}$$

$$PP_{c,n} = \frac{NC_n}{(NC)/j} \tag{3.9}$$

Where,

$n -$ eco-efficiency options $(1, 2, 3\ \cdots\ j)$

$PP_{e,n} -$ environmental preliminary portfolio position of option n

$PP_{c,n} -$ cost preliminary portfolio position of option n

– The preliminary positions have been improved by the environment to cost relevance factor in order to get a new position where environmental impacts and costs were balanced (Equation 3.10 and 3.11) (Kicherer et al., 2007).

$$PP'_{e,\alpha} = \left[\left(\sum PP_{e,\alpha}\right)/j + \left[PP_{e,\alpha} - \left(\left(\sum PP_{e,\alpha}\right)/j \right) \right] \cdot \sqrt{\left(R_{e,c}\right)} \right] / \left[\left(\sum PP_{e,\alpha}/j \right) \right] \quad (3.10)$$

$$PP'_{c,\alpha} = \left[\left(\sum PP_{c,\alpha}\right)/j + \left[PP_{c,\alpha} - \left(\left(\sum PP_{c,\alpha}\right)/j \right) \right] / \sqrt{\left(R_{e,c}\right)} \right] / \left[\left(\sum PP_{c,\alpha}/j \right) \right] \quad (3.11)$$

Where,

$PP'_{e,n}$ − environmental adjusted portfolio position of option n

$PP'_{c,n}$ − cost adjusted portfolio position of option n

Previous EEA studies have established that the complicated analysis of both the environmental and economic criteria for alternative selection was made more comprehensive and straightforward with an eco-efficiency portfolio (Kicherer et al., 2007; Landsiedel & Saling, 2002; Saling, 2005; Saling et al., 2002; Uhlman & Saling, 2010; Wall-Markowsk, Kicherer, & Saling, 2004). Such visualization helps in communicating the strategic selection of alternatives to stakeholders for an effective decision-making process.

3.7 Conclusion

This chapter presented the rationale and development of eco-efficiency analysis (EEA) framework for attaining environmental productivity and economic prosperity of RAPS in Western Australia. The analyses of ELCA and LCC separately cannot assist in the selection of appropriate improved RAPS options. The integration of these tools using eco-efficiency portfolio analysis avoids the dilemma as to whether to choose an option that is less environmentally friendly but more economical or to select one that is more environmentally friendly but less economical. These tools help in the recommendation of eco-efficient RAPS options and reflect the balance between these two pillars of sustainability (economics and environment). Finally, the proposed EEA framework can assist decision makers and energy planners in mitigating environmental impacts from electricity generation in an economically feasible way.

ELCA and LCC results are calculated in Chapter 4 to apply these in the EEA framework to determine an eco-efficient option for the solar PV-diesel hybrid systems in Marble Bar and Yungngora and for the wind-diesel hybrid system in Coral Bay.

Chapter 4

Life Cycle Assessment for Remote Area Power Supply System in Western Australia

4.1 Introduction

This chapter presents the application of life cycle assessment in the EEA framework to address the following research objectives.

Objective 2: To estimate the environmental impacts of upstream and downstream life cycle stages of the RAPS systems and identify their environmental hotspots

Objective 3: To select appropriate eco-efficiency strategies for the identified hotspots of the RAPS systems to further reduce environmental impacts

Objective 4: To assess the life cycle costs of the existing and improved RAPS options

Environmental life cycle assessment (ELCA) has been used to estimate the environmental impacts associated with the life cycle of RAPS systems in Western Australia. Australian life cycle inventories (LCIs) that consist of the inputs of mining to material production, power generation equipment manufacturing, construction, operation and maintenance, and eventual disposal have been developed following the power system design provided by Horizon Power (power distribution utility in remote Western Australian communities). The HOMER software has been used to estimate some LCI inputs such as the amount of diesel and renewable energy supply to meet the annual demand. Once the ELCA of the RAPS systems has been completed, 'hotspots' of significant environmental impact have been identified and eco-efficiency strategies have been selected to mitigate these impacts.

Using the same LCIs, life cycle costing (LCC) has been carried out to estimate the life cycle costs of both existing and improved RAPS options. The capital, operation and maintenance costs were estimated following the consultation with the power developers and reviewed published literature. Finally, the results from the ELCA and LCC analyses have been further analysed to assess the cost implications of the most environmentally friendly options.

4.2 Step 1: Environmental Life Cycle Assessment

4.2.1 Life Cycle Inventory

The development of LCIs is pre-requisite in carrying out life cycle environmental impacts. As discussed in Chapter 3, the LCIs include energy and material inputs for manufacturing the power generation equipment, transportation of system components, materials consumed during the operational period and disposal at the end of the life cycle of the RAPS systems. This section discusses the LCI development and details of the three hybrid systems.

4.2.1.1 Mining to Material Production and Equipment Manufacturing

The LCIs of mining to the manufacturing of equipment are developed using the specification of each equipment. Mass and energy balance information for the individual quantity of materials used for each equipment was obtained from published literature (Andrada et al., 2012; Arani, Karami, Gharehpetian, & Hejazi, 2017; Chen et al., 2016; Hong et al., 2016; H. C. Kim, Fthenakis, Choi, & Turney, 2012; Peña-Alzola, Sebastián, Quesada, & Colmenar, 2011; Petrillo et al., 2016; Schofield, 2011; Zhang, Zhou, Zhou, & Liu, 2016) and reports (MTU Friedrichshafen GmbH, 2003; Scania Industrial & Marine Engines, 2007; Shingleton, 2008; VERGNET, 2016). The mass of the constituent materials of each identified equipment and the energy required to manufacture them for the three hybrid systems are presented in Appendix B (Table B.1 to Table B.7)

4.2.1.2 Construction and Transportation

Most of the components were manufactured in Europe and China, while the remaining components were manufactured in other countries. Equipment transport is calculated using loading weights, travel distances and transport types. An overview of the mass of each equipment, transport locations and distances is shown in Appendix B (Table B.8 to Table B.10).

In the case of the construction stage, the LCIs are categorised into sub-stages including site preparation, installation of diesel generators, installation of RETs and transportation of construction equipment. The energy consumption for machinery (e.g. excavator, grader and forklift) and electric tools for construction have been estimated and presented in MJ. Mass and energy balance information for the individual quantity of construction materials has been obtained from equipment manuals (Chermak, 2009; Clenergy; Clenergy; MTU Onsite Energy Corporation, 2015; Shingleton, 2008). Finally, information on the transportation of construction materials and equipment to the construction site is estimated and presented in terms of tonnes-km as shown in Appendix B (Table B.11 to Table B.13).

4.2.1.3 Operation

The diesel electricity generation, diesel consumption and renewable energy generation have been estimated over a lifespan of 25 years for the hybrid solar PV-diesel hybrid systems in Marble Bar and Yungngora and 20 years for the hybrid wind-diesel hybrid system in Coral Bay using HOMER software. As discussed in section 3.3.2.3, the annual load demand, solar irradiation and wind speed data of location-specific RAPS and the technical specifications of the equipment utilised for electricity generation including diesel generators, solar PV panels, wind turbine, flywheel energy storage, batteries and inverters were entered into HOMER software. The outputs generated from the HOMER software and their corresponding units are as follows.

- Renewable energy power generation (MWh)
- Diesel power generation (MWh)
- Diesel consumption (m^3)
- Diesel engine operation (hours)

Tables B.14, B.15 and B.16 in Appendix B show the results generated from the simulation of the three hybrid systems in HOMER software.

The fuel transport from the diesel refinery to the hybrid system site has been estimated. The diesel used for power generation in the case study sites is refined in the Kwinana Oil Refinery and then distributed by local retailers such as Recharge Petroleum and Refuel Australia. Fuel transport has also been calculated in tonnes-km and approximated with the use of diesel mass, travel distances and transport types (e.g. truck and ship). Finally, the consumption of engine oil and coolant have been estimated over the life cycle. The amount of consumables used for the diesel engine is a function of the equipment operational hours. Therefore, these were calculated using the diesel engine operation information estimated from HOMER software and the technical specifications of the engines used for power generation.

Table 4.1 presents the operational LCIs of solar PV-diesel hybrid system in Marble Bar. An average of 6.09 kWh/m^2/day of solar irradiation generated annual solar PV power between 677.47 MWh and 720.42 MWh to supply an annual load demand of 2,125.58 MWh. The solar power penetration in the total energy mix is only 22.63%. The annual diesel power generation varies between 1,630.66 MWh and 1,658.03 MWh and consumes an average of 457.39 m^3 of diesel annually. It was known from Vi Garrood of Horizon Power (personal communication) that these results are comparable to the forecast by Horizon Power of 2016/17 Marble Bar diesel power generation.

Table 4.1 Summary of estimated quantities of energy and materials during the operational stage of the hybrid system in Marble Bar

Material/Energy	Unit	Quantity
Diesel	m^3	11,434.63
Engine oil	m^3	40.39
Coolant	m^3	20.19
Diesel power generation	MWh	41,113.75
Transportation of diesel to site	tonnes-km	19,078,005.53

*The detailed calculations of the inputs during the operation stage of the hybrid system in Marble Bar are described in detail in Appendix B (Table B.14, Table B.17 and Table B.18).

The LCIs during the operational stage of the solar PV-diesel hybrid system in Yungngora are shown in Table 4.2. An average of 6.21 kWh/m^2/day of annual solar irradiation generated between 329.45 MWh and 398.46 MWh to meet the annual load demand of 1,735.02 MWh. The recorded renewable fraction in the total electricity mix is only 18.92%. The annual power generation from the diesel engines varies from 1,379.51 MWh to 1,434.35 MWh and consumes diesel annually at an average of 390.65 m^3. These results are almost similar to the forecast estimated by Horizon Power in Yungngora (personal communication with Vi Garrood of Horizon Power). The forecasted diesel power generation and diesel consumption are 1,527 MWh and 400 m^3, respectively.

Table 4.2 Summary of estimated quantities of energy and materials during the operation of the hybrid system in Yungngora

Material/Energy	Unit	Quantity
Diesel	m^3	9,766.36
Engine oil	m^3	19.96
Coolant	m^3	10.65
Diesel power generation	MWh	35,167.80
Transportation of diesel to site	tonnes-km	23,741,913.82

*The detailed calculations of the inputs during the operation stage of the hybrid system in Yungngora are described in detail in Appendix B (Table B.15, Table B.17 and Table B.18)

The inventories of the operational stage of the wind-diesel hybrid system in Coral Bay is shown in Table 4.3. The three 275 kW Vergnet wind generators produce an annual wind electricity of 1,391.50 MWh for an annual average wind speed of 6.8 m/s to supply the load of 3,261.23 MWh. This wind power can potentially serve 42.67% of the total load demand, but the fraction of the actual wind electricity utilised is only 36.65%. The diesel engines consume 570.37 m^3 of diesel to generate 2,065 MWh of electricity annually. It was known from Vi Garrood of Horizon Power (personal communication) that these results are comparable with the Horizon Power 2016/17 forecast of electricity generation and diesel consumption estimated in Coral Bay. The forecasted wind generation, diesel power generation and diesel consumption are 1,237 MWh, 2,148 MWh and 570 m^3, respectively.

Table 4.3 Summary of estimated quantities of energy and materials during the operation stage of the hybrid system in Coral Bay

Material/Energy	Unit	Quantity
Diesel	m^3	11,407.48
Engine oil	m^3	36.86
Coolant	m^3	18.43
Diesel power generation	MWh	41,317.76
Transportation of diesel to site	tonnes-km	10,991,626.02

*The detailed calculations of the inputs during the operation stage of the hybrid system in Coral Bay are described in detail in Appendix B (Table B.16 to Table B.18).

4.2.1.4 Maintenance

The mass of materials for equipment cleaning and BOS replacement are estimated over the life cycle of the hybrid systems. The transportation information in terms of tonnes-km for transferring the replaced equipment has been approximated using equipment weights, travel distances and mode of transport, while the transportation of personnel for overhaul and maintenance in person-km has been estimated using the number of personnel, travel distance and transport type. A summary of the estimated inventory of materials, energy and transport during the maintenance stage of the hybrid systems is shown in Appendix B (Table B.19 to Table B.20).

4.2.2 Estimation of Environmental Impacts of RAPS in Western Australia

The LCIs in section 4.2 have been used to estimate the environmental impacts of each hybrid system. Firstly, predominant impacts that contribute at least 5% on the normalised impacts of RAPS systems have been considered for hotspot analysis. Secondly, the environmental hotspots of the significant impacts have been identified for possible environmental improvement through eco-efficiency strategies.

4.2.2.1 Solar PV-diesel hybrid system in Marble Bar

The resulting environmental impacts of the upstream and downstream stages of the hybrid system in Marble Bar have an estimated global warming potential of 349 kg CO_2 eq, mineral depletion of 0.0006 kg Sb eq, fossil fuel depletion of 5 kg Sb eq, land use and ecological diversity of 0.0007 Ha a, water depletion of 1.7 m^3 H_2O, eutrophication of 0.7 kg PO_4 eq, acidification of 3.4 kg SO_2 eq, freshwater ecotoxicity of 1 kg 1,4-DB eq, marine ecotoxicity of 1.3 kg 1,4-DB eq, terrestrial ecotoxicity of 0.02 kg 1,4-DB eq, photochemical smog of 5 kg NMVOC, ozone depletion of 9E-5 kg CFC-11 eq, ionising radiation of 0.7 kBq U235 eq, human toxicity of 27 kg 1,4-DB eq and respiratory inorganics of 0.6 kg $PM_{2.5}$ eq per MWh of electricity supplied. The breakdown of these results in terms of life cycle stages is presented in Appendix C (Table C.1).

Following the procedure in section 3.3.3, the impact values have been divided by a reference value for each environmental impact to determine the significance of the calculated impacts. This normalisation process calculates the relative contribution of a potential environmental impact (e.g. global warming potential) to the overall impact in Australia. In this study, normalisation is based on equivalent inhabitants per year for each impact category (Bengtsson & Howard, 2010b). Figure 4.1 presents the normalisation results of each environmental impact. The breakdown of the normalised results into life cycle stages are shown in the Appendix C (Table C.2).

The normalised results show that the hybrid system would have a total equivalent impact of 0.235 inhabitant per year. Photochemical smog appears to be the predominant environmental impact, accounting for 29% of the total normalised impact. The second biggest contributor to the total impact is ozone depletion potential, which accounts for 19% of the overall normalised impact. The next significant impacts are eutrophication, acidification, fossil fuel depletion, respiratory inorganics and global warming potential, accounting for 15%, 12%, 7%, 5.9% and 5%, respectively. These environmental impacts were found to be significant due to their large contribution to total Australian impact levels. Further investigation of these impacts has been conducted to identify the environmental hotspots.

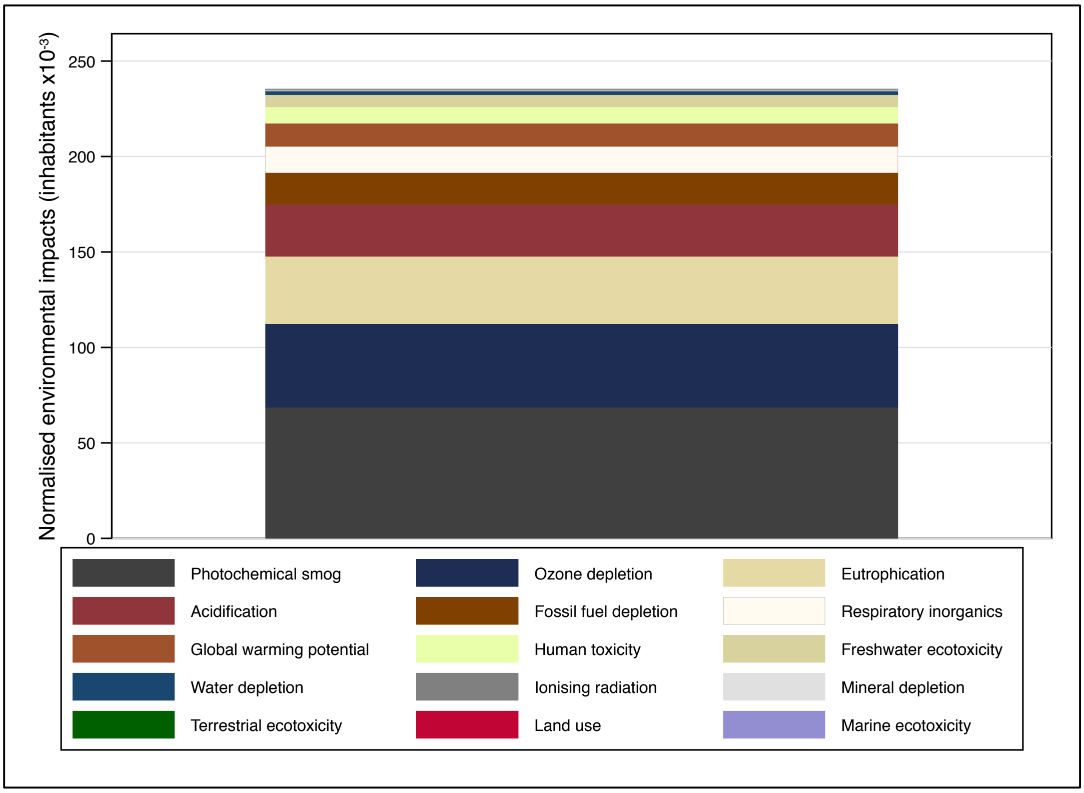


Figure 4.1 Normalised impact assessment results of a hybrid system in Marble Bar

Hotspot analysis of significant environmental impacts of the solar PV-diesel system in Marble Bar

The operational stage of the hybrid system was found to contribute 95% to global warming potential, 98% to fossil fuel depletion, 95% to eutrophication, 98% to acidification, 99%

to photochemical smog, 96% to ozone depletion potential, and 96% to respiratory inorganics (Figure 4.2). This life cycle stage was further broken down to identify the specific processes or inputs that made this an environmental hotspot.

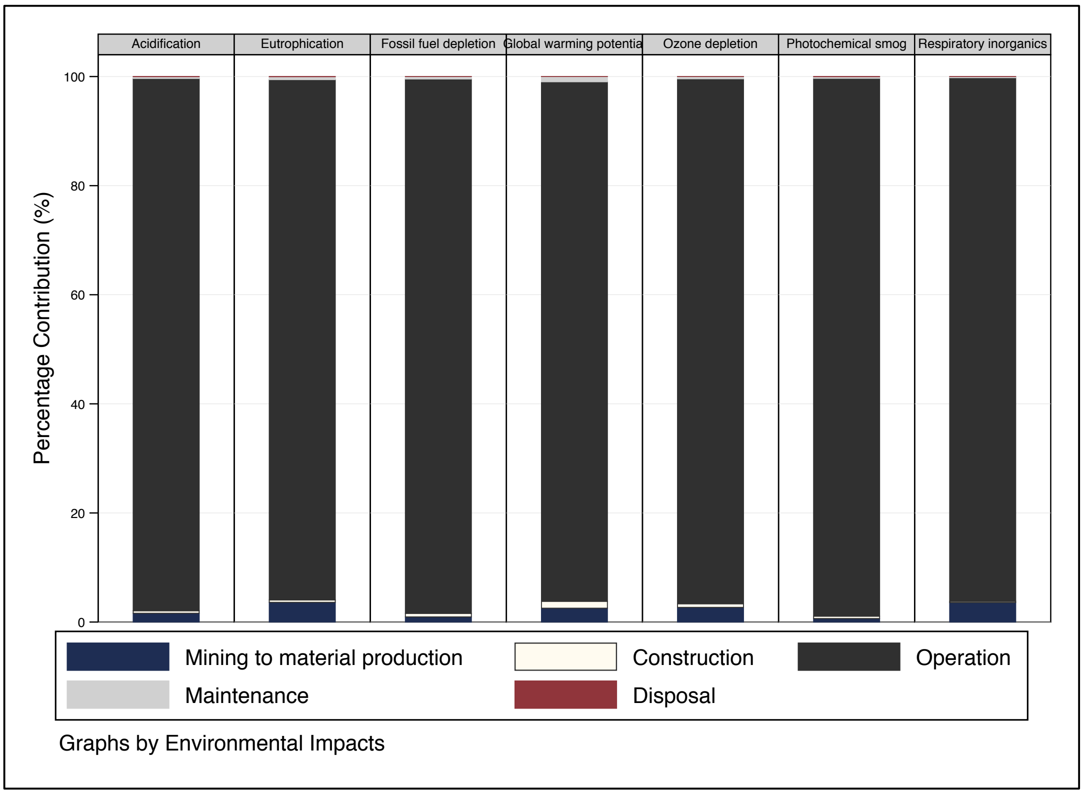


Figure 4.2 Breakdown of environmental impacts per life cycle stage for a solar PV-diesel hybrid system in Marble Bar (FU = 1 MWh of electricity generation)

Figure 4.3 shows the results of the flow networks generated in SimaPro software that gives the breakdown of the impacts of the operational stage. The results show that the hotspot for each impact category is either the production of fossil fuel or combustion of diesel.

Diesel combustion has the highest contribution in global warming potential (208 kg CO_2 eq/MWh, 63%), eutrophication (0.5 kg PO_4 eq/MWh, 78%), acidification (2 kg SO_2/MWh, 65%), photochemical smog (4 kg NMVOC eq/MWh, 83%) and respiratory inorganics (0.5 kg $PM_{2.5}$/MWh, 86%). The main reason for this is due to the large emission of greenhouse gases (GHGs) and particulates. Diesel production is the second largest contributor to global warming potential (100 kg CO_2 eq/MWh, 30%), eutrophication (0.1 kg PO4 eq/MWh, 18%), acidification (1 kg SO_2/MWh, 31%), photochemical smog (0.7 kg NMVOC/MWh, 13%) and respiratory inorganics (0.08 kg $PM_{2.5}$/MWh, 13%). Whilst the production of diesel is not as emission intensive as diesel combustion, the large amount of diesel used for power generation makes it an environmental hotspot.

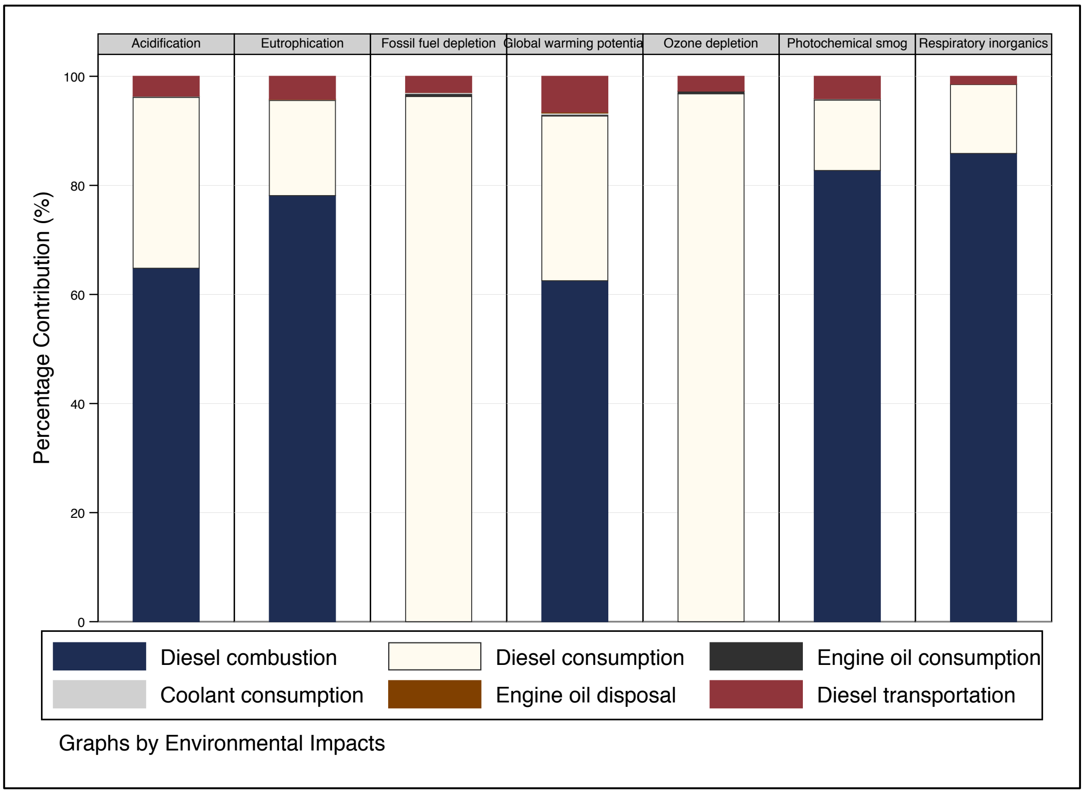


Figure 4.3 Breakdown of environmental impacts of the operational stage for a solar PV-diesel hybrid system in Marble Bar (FU= 1 MWh of electricity generation)

Diesel combustion has no influence on fossil fuel depletion and ozone depletion since this stage only involves the emission of GHGs and particulates. However, diesel production is considered a hotspot given its contribution to fossil fuel depletion (5 kg Sb eq/MWh, 96%) and ozone depletion (8E-5 kg CFC-11 eq/MWh, 97%).

The transportation of fuel to power generating sites has a low contribution (1 – 7%) to all environmental impacts. The power distribution utility in Marble Bar sourced their diesel from the Kwinana refinery and transported by ship from Kwinana port to Wedgefield port, and then transported by truck from the port to the site. The estimated impact from this process is minimal. Analysis of different routes for diesel source and possibility of obtaining diesel from another state or country are beyond the scope of this study.The stages including engine oil production and disposal and coolant production have by far the least contribution (<0.5%) to all environmental impacts. The reason for this is due to the fact that engine oil and coolant are minimally used during the maintenance of the diesel engines.

4.2.2.2 Solar PV–diesel hybrid system in Yungngora

The impact assessment results of the upstream and downstream stages of the hybrid system in Yungngora were found to have an estimated global warming potential of 368 kg CO_2 eq, mineral depletion of 0.0008 kg Sb eq, fossil fuel depletion of 5 kg Sb eq, land use and ecological diversity 0.0007 of Ha a, water depletion of 2 m^3 H_2O, eutrophication of 0.7 kg PO_4 eq, acidification of 3.5 kg SO_2 eq, freshwater ecotoxicity of 0.6 kg 1,4-DB eq, marine ecotoxicity of 0.8 kg 1,4-DB eq, terrestrial ecotoxicity of 0.01 kg 1,4-DB eq, photochemical smog of 5.5 kg NMVOC, ozone depletion of 9E-5 kg CFC-11 eq, ionizing radiation of 0.4 kBq U235 eq, human toxicity of 22 kg 1,4-DB eq and respiratory inorganics of 0.6 kg $PM_{2.5}$ eq (Table C.3).

The normalised impact values are presented in Figure 4.4 and the breakdown of these results into life cycle stages is shown in Appendix C (Table C.4).The results show that the hybrid system would have a total equivalent impact of 0.297 inhabitant per year (Figure 4.4).

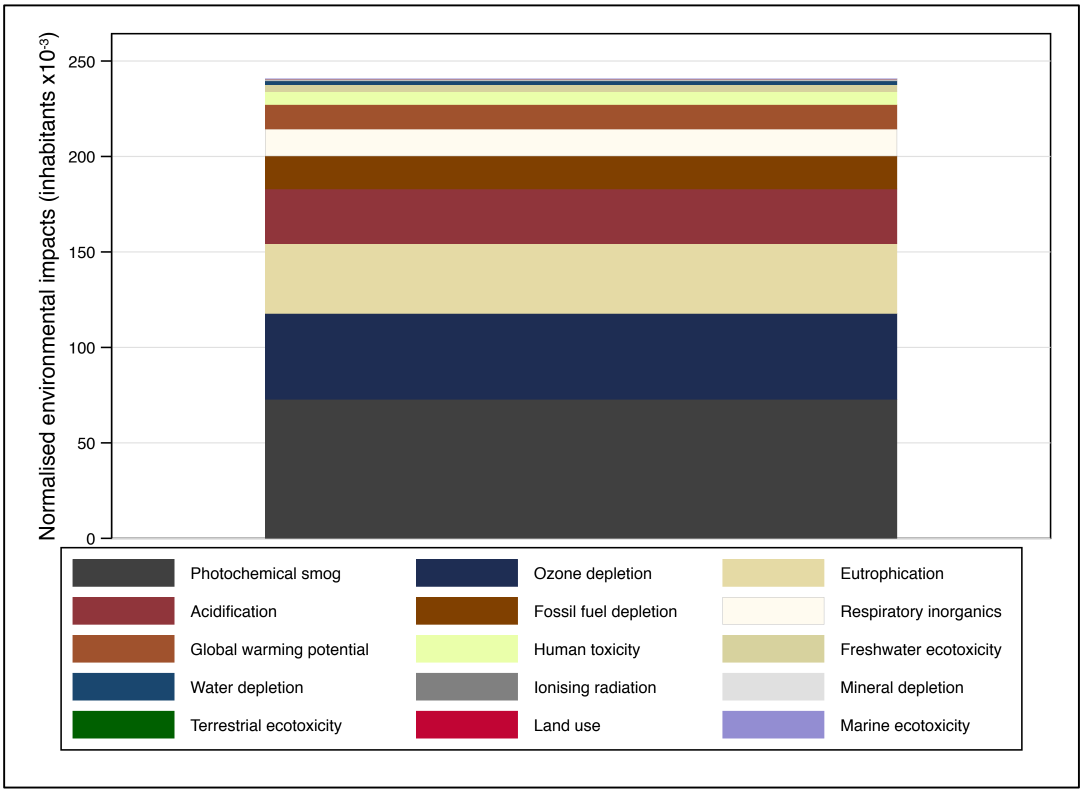


Figure 4.4 Normalised impact assessment results of a hybrid system in Yungngora

Of all environmental impacts, photochemical smog has the largest influence with a contribution of 30% to the total normalised impact. The other impacts that were also considered relevant include the ozone depletion potential, eutrophication, acidification, fossil fuel depletion, respiratory inorganics and global warming potential, which contribute 19%, 15%, 12%, 7% and 6% respectively to the overall normalised impacts. The same impact categories were also found relevant for the hybrid systems in Marble Bar.

Hotspot analysis of significant environmental impacts of the solar PV-diesel system in Yungngora

The operational stage of the hybrid system was found to contribute 98% to global warming potential, 99% to fossil fuel depletion, 98% to eutrophication, 98% to acidification, 99% to photochemical smog, 99% to ozone depletion and 99% to respiratory inorganics (Figure 4.5). Further investigation was conducted to determine the specific processes or inputs that made this stage an environmental hotspot.

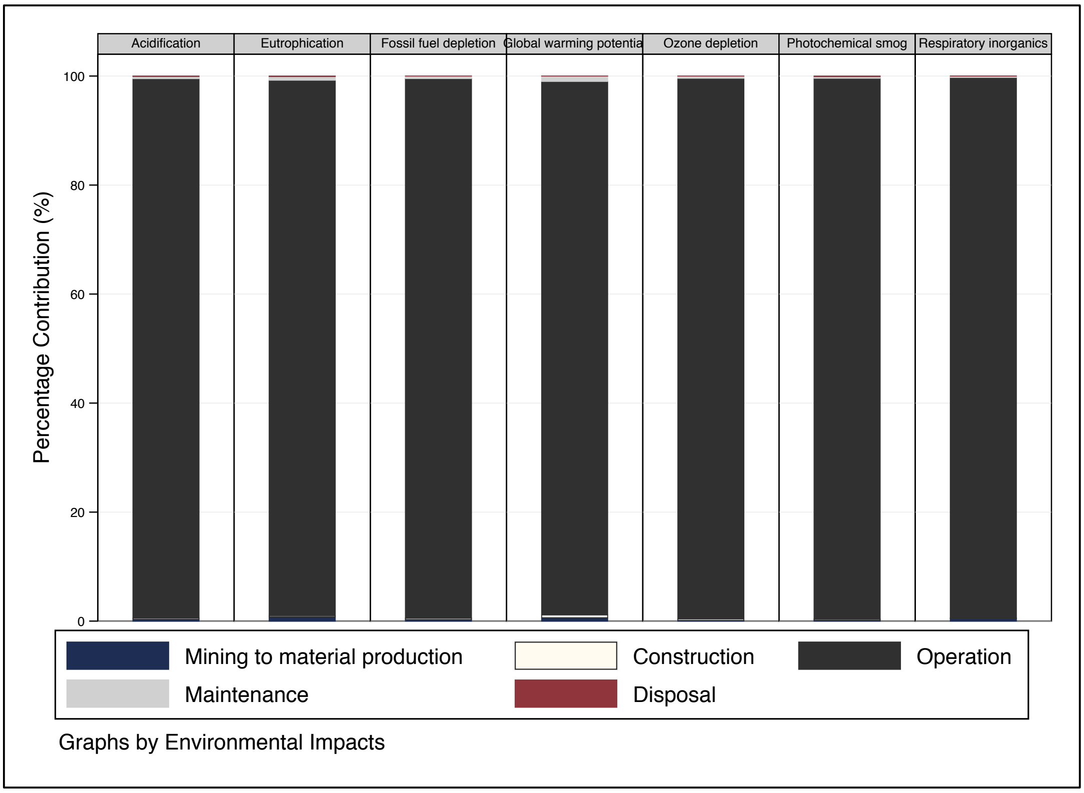


Figure 4.5 Breakdown of environmental impacts per life cycle stage for a solar PV-diesel hybrid system in Yungngora (FU = 1 MWh of electricity generation)

Figure 4.6 shows the results of the network flows during the operation of the hybrid system. The production of fossil fuel and combustion of diesel were found to be the largest contributor to the environmental impacts.

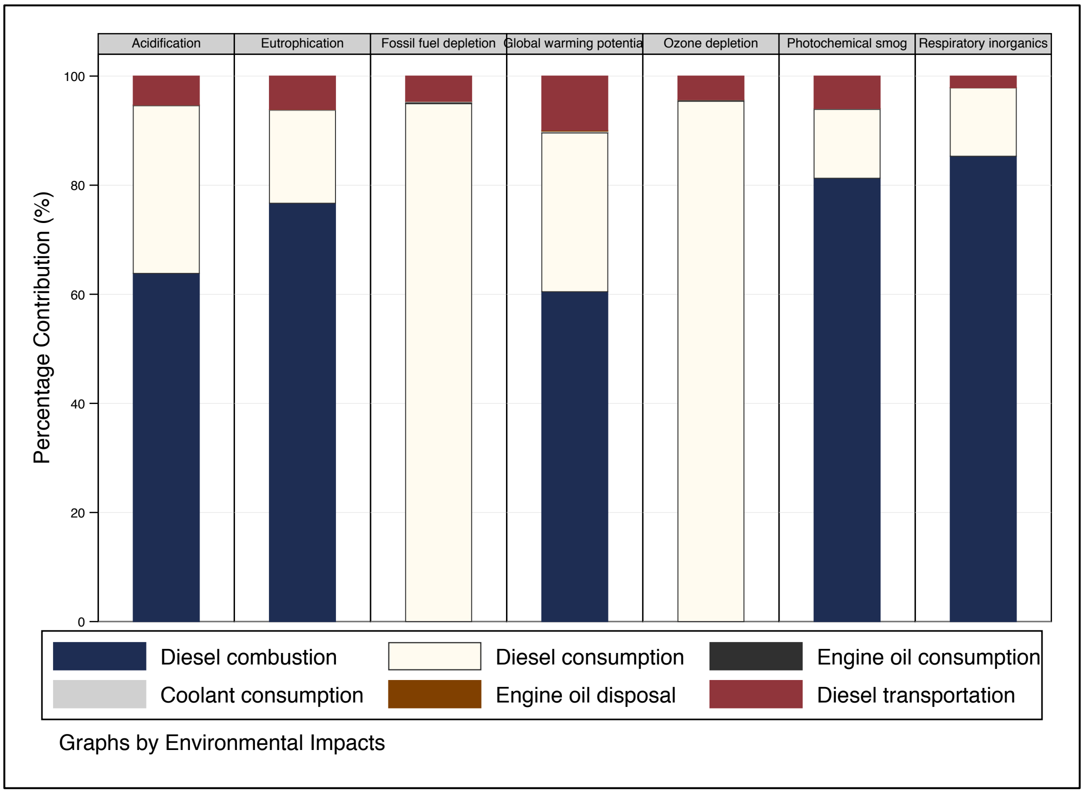


Figure 4.6 Breakdown of environmental impacts of the operational stage for a solar PV-diesel hybrid system in Yungngora (FU= 1 MWh of electricity generation)

Similar to the hybrid system in Marble Bar, the large emission of GHGs from the combustion of diesel results in significant global warming potential (218 kg CO_2 eq/MWh, 85%), eutrophication (0.5 kg PO_4 eq/MWh, 77%), acidification (2 kg SO_2/MWh, 64%) and photochemical smog (4.4 kg NMVOC eq/MWh, 60%) while the large emission of particulates results in high respiratory inorganics (0.5 kg $PM_{2.5}$/MWh, 81%). The production of diesel is the next hotspot that considerably contributes to the same impacts during the operational stage and this was attributed to the large amount of diesel consumed for hybrid electricity generation.

Diesel combustion was found not to contribute to ozone depletion and fossil fuel depletion as this stage only involves the emission of GHGs and particulates. However, the production of diesel was found as the major contributor to fossil fuel depletion (5 kg Sb eq/MWh, 95%) and ozone depletion (9E-5 kg CFC-11 eq/MWh, 95%).

The transportation of fuel has a minimal influence on all environmental impacts (2 – 10%). It was assumed that the power distribution utility in Yungngora sourced its diesel from the Kwinana refinery and delivered by ship from Kwinana port to Broome port and then transported by truck from the port to the power generating site. This assumption considered the least possible impact estimated from fuel transportation, as the fuel is sourced from the closest refinery.

The stages including engine oil production, coolant production and engine oil disposal accounted for the least impact (<0.3%) in all environmental impacts. Similar to Marble Bar, it happens because of the fact that a small amount of engine oil and coolant is used for maintaining the operational performance of the diesel engines.

4.2.2.3 Wind–diesel hybrid system in Coral Bay

ELCA has been used to assess the environmental performance of a wind-diesel hybrid system. The impact assessment results and its breakdown into life cycle stages for the hybrid system in Coral Bay are shown in the Appendix C (Table C.5). It was found that this system has an estimated global warming potential of 295 kg CO_2 eq, mineral depletion of 0.0005 kg Sb eq, fossil fuel depletion of 4 kg Sb eq, land use and ecological diversity of 0.0003 Ha a, water depletion of 1.5 m^3 H_2O, eutrophication of 0.5 kg PO_4 eq, acidification of 3 kg SO_2 eq, freshwater ecotoxicity of 1 kg 1,4-DB eq, marine ecotoxicity of 1 kg 1,4-DB eq, terrestrial ecotoxicity of 0.01 kg 1,4-DB eq, photochemical smog of 4 kg NMVOC, ozone depletion of 7E-5 kg CFC-11 eq, ionising radiation of 2 kBq U235 eq, human toxicity of 23 kg 1,4-DB eq and respiratory inorganics of kg $PM_{2.5}$ eq for every MWh of electricity generation.

The total normalised impact of the hybrid power supply system has an equivalent impact of 0.194 inhabitants per year (Figure 4.7). The equivalent normalisation values of the presented figure are shown in Appendix C (Table C.6). Similar to the hybrid system in Marble Bar and Yungngora, photochemical smog, ozone depletion, eutrophication potential, acidification potential, fossil fuel depletion, respiratory inorganics and global warming potential were found to be the predominant environmental impacts. These impacts account for 92% of the overall normalised values, while the rest of the impacts including human toxicity, freshwater ecotoxicity, water depletion, ionising radiation, mineral depletion, terrestrial ecotoxicity, land use and marine ecotoxicity have minimal influence. These environmental impacts were further investigated for identification of hotspots.

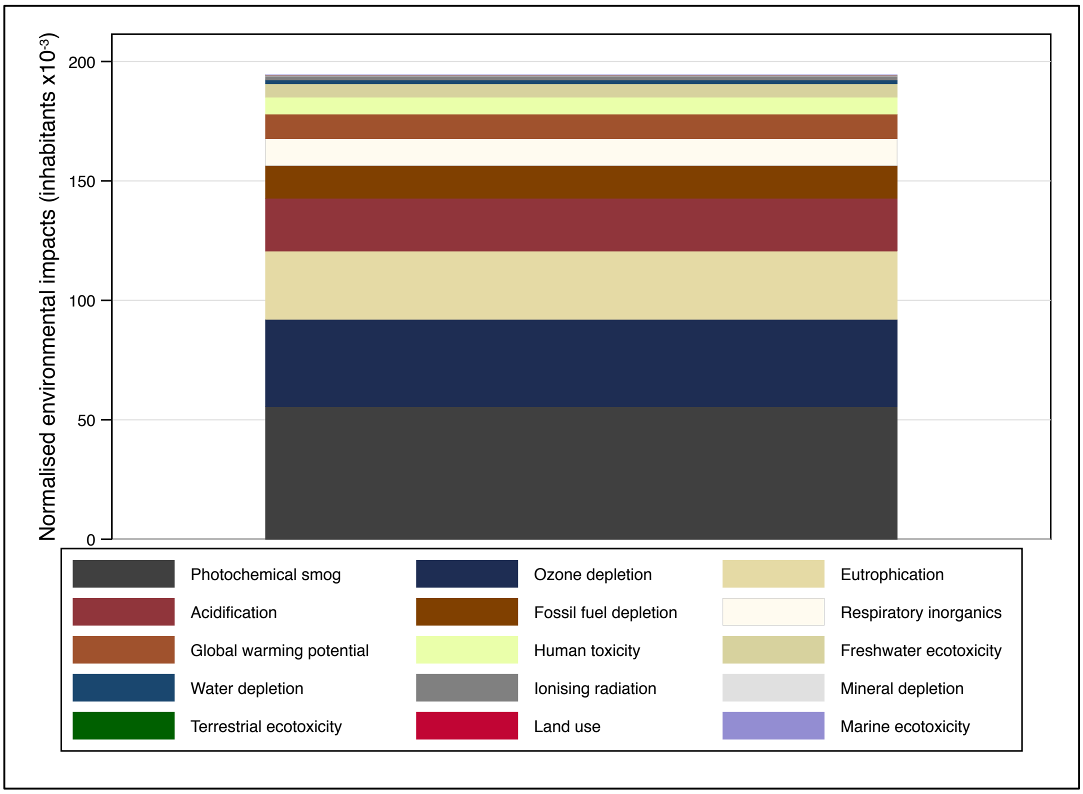


Figure 4.7 Normalised impact assessment results of a hybrid system in Coral Bay

Hotspot analysis of significant environmental impacts of the wind-diesel hybrid system in Coral Bay

The hotspot analysis has shown that the life cycle stage that contributed the largest to the significant impacts was the operational stage (Figure 4.8). It was found that this has a contribution of 96% to global warming potential, 98% to fossil fuel depletion, 96% to eutrophication, 98% to acidification, 99% to photochemical smog, 97% to ozone depletion and 96% to respiratory inorganics. Further hotspot analysis was conducted on the operational stage to investigate the emission-intensive operational processes and inputs that can be improved to reduce these impacts.

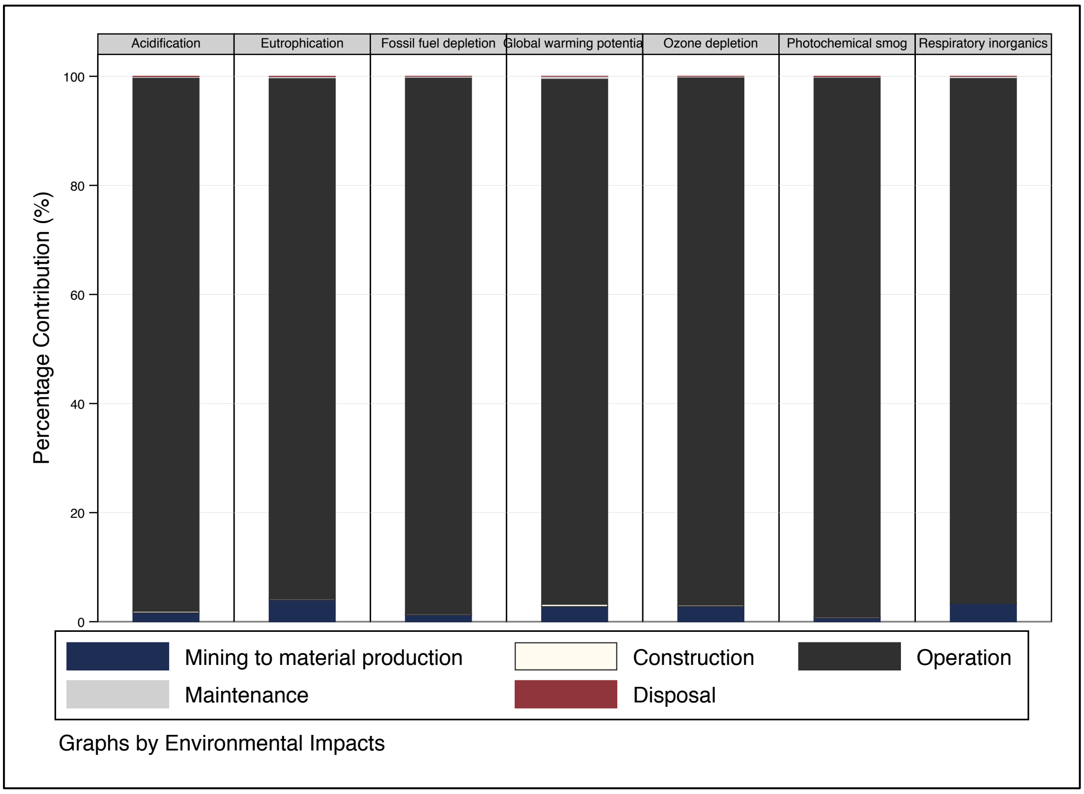


Figure 4.8 Breakdown of environmental impacts per life cycle stage for a wind-diesel hybrid system in Coral Bay (FU = 1 MWh of electricity generation)

The analysis of the network flows in SimaPro software is presented in Figure 4.9. This table shows the process wise breakdown of impacts of the power supply system during the operational stage wherein diesel production and diesel combustion account for the largest share of each environmental impact.

The combustion of diesel is the largest contributor of most environmental impacts. The contribution of this process to the impacts including photochemical smog (3 kg NMVOC/MWh), eutrophication (0.4 kg PO_4 eq/MWh), acidification (2 kg SO_2 eq/MWh), respiratory inorganics (0.4 kg $PM_{2.5}$ eq/MWh) and global warming potential (170 kg CO_2eq/MWh) are 81%, 77%, 64%, 85% and 60%, respectively. These results are due to the GHG and particulate emission-intensive combustion of diesel.

The production of diesel is the next hotspot that contributes considerably to global warming potential (81 kg CO_2 eq/MWh, 29%), eutrophication (0.09 kg PO_4 eq/MWh, 17%), acidification (0.8 kg SO_2 eq/MWh, 31%), photochemical smog (0.5 kg NMVOC/MWh, 13%) and respiratory inorganics (0.06 kg $PM_{2.5}$ eq/MWh, 13%). The reason for this process to emerge as a hotspot is due to the large amount of diesel used for power generation.

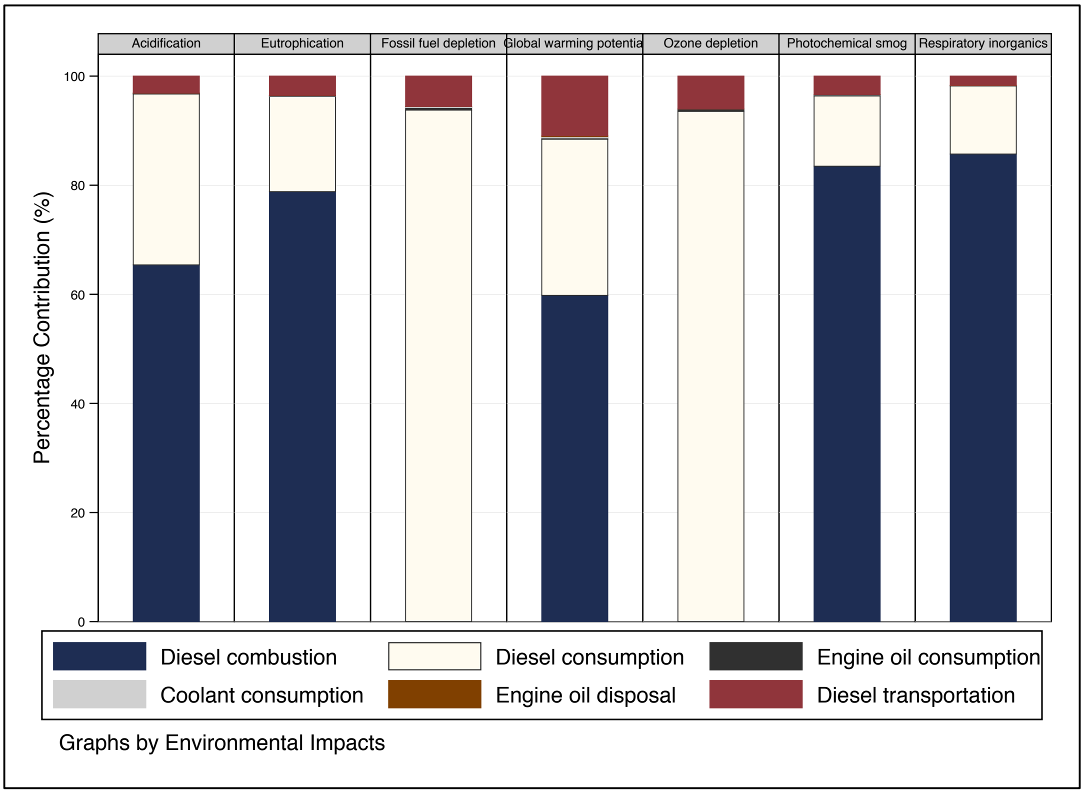


Figure 4.9 Breakdown of environmental impacts of the operational stage for a wind-diesel hybrid system in Coral Bay (FU= 1 MWh of electricity generation)

The combustion of diesel was found not to contribute to ozone depletion potential and fossil fuel depletion. However, the contribution of diesel production accounted more than 90% to each environmental impact.

The next process that contributes considerably across all environmental impacts is the transportation of fuel (2% to 11%). The diesel used to operate the power station was sourced from the Kwinana refinery and then delivered to the power generating site via truck. The impacts estimated from this process are at a minimum since the principle of proximity was assumed in all transportation processes. In the case when the fuel is supplied by a distributor from another location, the impact from fuel transportation may increase but this additional analysis is beyond the scope of the study.

The impacts from the processes including engine oil production, coolant production and engine oil disposal have a minimal influence in all environmental impacts. Similar to

Marble Bar and Yungngora, the negligible influence of these processes is due to the minimal use of engine oil and coolant during the operational stage.

4.2.3 Discussion

A comparative analysis of three hybrid systems has been conducted to determine the hybrid system that offers the best environmental performance. The characterised values of environmental impacts per MWh of electricity generation show that Coral Bay has environmental impacts that are lower than Marble Bar and Yungngora (Table C.7). Although the total individual impacts (*numerator*) associated with the whole life cycle of the hybrid system in Coral Bay are higher than Marble Bar and Yungngora, its larger power supply (*denominator*) reduced these impacts for every MWh of power generated.

The normalised values of environmental impacts for all hybrid systems show that photochemical smog was the most predominant impact. This is due to the significant contribution of the emitted non-methane volatile organic compounds (NMVOCs) to the Australian NMVOC level. The other predominant impacts are ozone depletion, eutrophication, acidification, fossil fuel depletion, respiratory inorganics and global warming potential.

The main reason for the better environmental performance of the hybrid system in Coral Bay is due to its larger installed renewable capacity (875 kW_p) than Marble Bar (304 kW_p) and Yungngora (175 kW_p). The fraction of electricity generation from the wind generators in Coral Bay over their life cycle is 37%, which results in less power required from diesel engines. In Marble Bar and Yungngora, the fractions of electricity generation from solar PVs are only 21% and 19%, respectively. Diesel production and combustion is still the hotspot (>88%) when the share of renewable energy in the mix is at least 19%. Therefore, there is a need to increase the share of renewable energy in the electricity mix significantly if environmental impacts of these RAPS systems are to be significantly reduced (Figure 4.10).

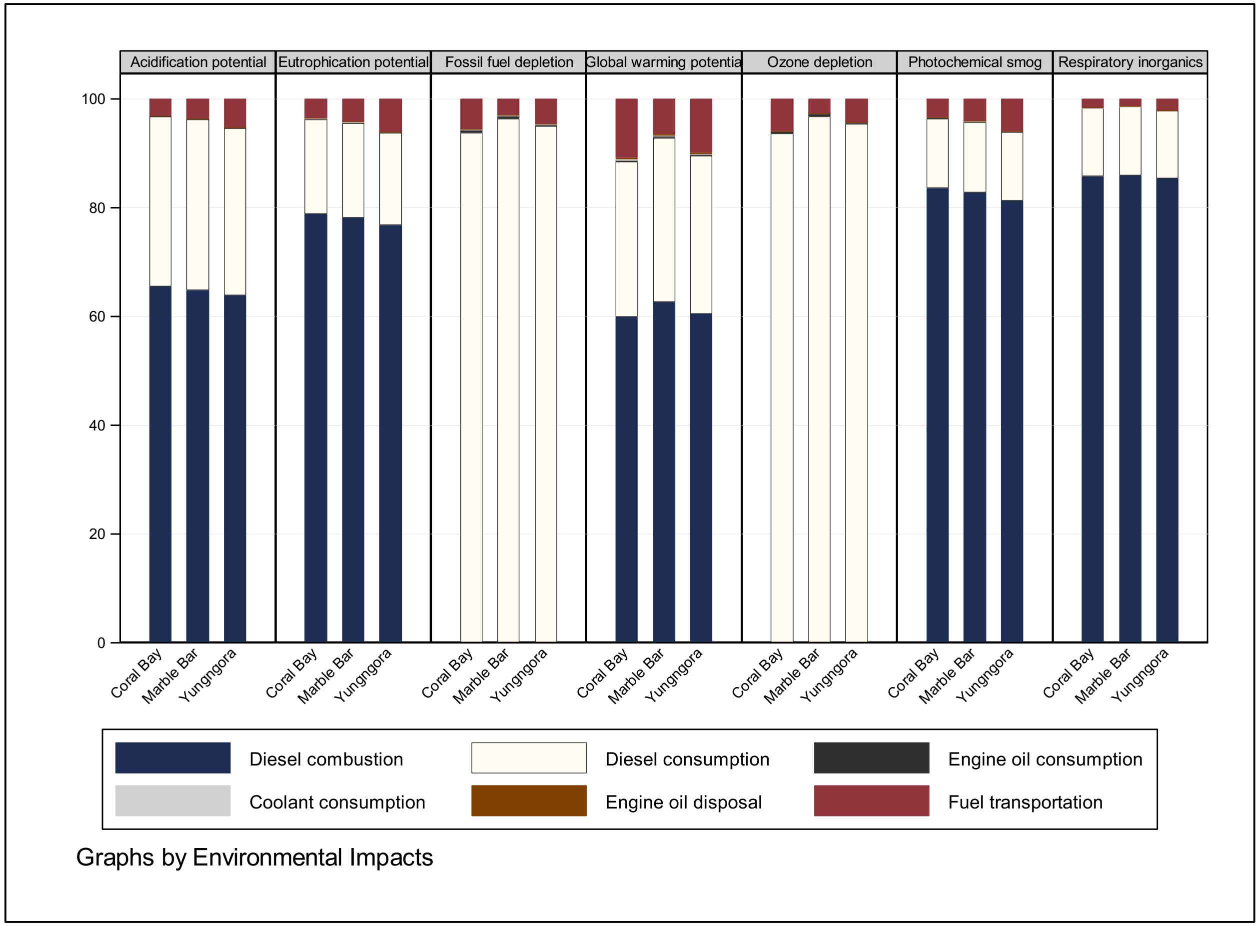


Figure 4.10 Percentage contribution of the operational processes of the hybrid systems in Marble Bar, Coral Bay and Yungngora

The results of this research are similar to previous ELCA studies on RAPS systems. Smith et al. (2015) identified that the combustion of diesel in a hybrid system contributes 76% to global warming potential, 54% to fossil fuel depletion and 53% to acidification. Schofield (2011) deduced that a low renewable energy penetration in a hybrid system may not completely offset the environmental impacts from diesel combustion.

The findings of this research has also been compared with other RAPS and stand-alone systems (SAS). The mining to material production stage was found to be an environmental hotspot for RAPS systems that uses 100% RETs (Petrillo et al., 2016). The production of solar PV modules was found to contribute 97% to primary energy consumption and 97% to GHG emissions, which were attributed to the large production of silicon, copper and toxic chemicals (Fthenakis & Kim, 2011). Ardente et al. (2008) found that high volume of steel to manufacture wind generators significantly contribute 92% to primary energy consumption that causes large GHG and particulate emissions. In the current research, the contribution of the mining to manufacturing production of power generating equipment (e.g. solar PV and wind) to all environmental impacts have minimal influence (<10%). due to the larger impact contribution of the operational stage.

The findings in this study have important implications on the development of eco-efficiency strategies. Significant environmental impact reduction would be achieved if these strategies were developed to manage the operational stage (combustion of diesel and production of fossil fuel) of the hybrid system.

4.2.4 Summary of Impact Assessment Results of RAPS in Western Australia

The environmental life cycle results of the solar PV-diesel hybrid systems in Marble Bar and Yungngora and the wind-diesel hybrid system in Coral Bay were summarised and recommendation of location and system specific eco-efficiency strategies have been made.

- Photochemical smog, ozone depletion, acidification, eutrophication, fossil fuel depletion, respiratory inorganics and global warming potential have been identified as significant impacts in evaluating the environmental performance of a hybrid system.

- The operational stage of the hybrid systems has the largest contribution to all significant impacts. The impacts from mining to material production, construction, maintenance and end-of-life disposal are found to have minimal influence on the life cycle environmental impacts.

- During the operational stage, the production of fossil fuels and combustion of diesel have the highest contribution to all environmental impacts.

The next section will explore potential eco-efficiency strategies to reduce the impacts from the identified hotspots for the three hybrid systems in Western Australia.

4.3 Step 2: Identification of Eco-Efficiency Strategies

This section discusses the development and implementation of potential eco-efficiency strategies to achieve research objective 3 of the study. This endeavours to treat the identified hotspots of the hybrid systems in order to generate improved RAPS options with reduced environmental impacts. The following discussions present the strategies investigated in the study.

1. ***Reducing load restrictions on diesel engines***
   (Eco-efficiency objective: Reduce material and energy intensity, Maximise sustainable use of renewable resources)

   The improvement in the operational characteristics of a diesel engine can potentially increase the share of renewable energy in the generation mix of a hybrid system. The diesel engines that can operate at low load are more suitable for use in a hybrid system (ARENA, 2014). As a result, the wastage of excess electricity generation from RETs can be avoided by optimising diesel power generation (Meyer, 2015).

   Diesel engine manufacturers usually set the operating limit of the equipment at 30% output (ARENA, 2014; Meyer, 2015). Nayar (2010) and Jabeck (2014) indicated that operating the diesel engines at its lower limit for an extended period not only causes engine damage but also reduces fuel efficiency and increases maintenance costs. In consultation with Vi Garrood of Horizon Power (personal communication), it was stated that the load of diesel engines can be safely decreased by up to 10% of the rated capacity in Marble Bar and Coral Bay and up to 20% of the rated capacity in Yungngora. For new hybrid systems in Western Australia or elsewhere, the technical characteristics of the diesel engines must be investigated first before purchasing so as to enable higher renewable penetration without damaging the diesel engines or affecting its performance.

2. ***Integrating exhaust gas recirculation***
(Eco-efficiency objective: Reduce material and energy intensity)

Exhaust gas recirculation (EGR) has been found to be a commonly used method to improve engine efficiency by redirecting some of the cooled exhaust gases into the air intake of a diesel engine (Kech, Schmidt, Philipp, & Rall, 2011). This can potentially reduce the specific fuel consumption by 5% to 8% (Reifarth, 2010; Shakti Sustainable Energy Foundation, 2014) and nitrous oxide (N_2O) emissions by 25% to 40% (Jääskeläinen & Khair, 2012; Kolbenschimdt Pierburg Group; Muncrief, Rooks, Cruz, & Harold, 2008; Shakti Sustainable Energy Foundation, 2014).

This current study considered the incorporation of EGR in the diesel engines to reduce the specific fuel consumption by 8% and N_2O emissions by 40%. The maximum potential for operational improvement and N_2O emission savings have been assumed to demonstrate the maximum potential environmental impact reduction due to this eco-efficiency strategy. Table 4.4 shows the potential improvement in the specific fuel consumption of the MTU Detroit and Scania diesel engines currently being used in the hybrid systems.

Table 4.4 Specific fuel consumption (L/kWh) of diesel engines before and after integrating EGR

Power Output	**Before Integrating EGR**		**After Integrating EGR**	
	MTU Detroit	**Scania**	**MTU Detroit**	**Scania**
100% of capacity	86	71	79	65
75% of capacity	65	55	60	50
50% of capacity	45	38	42	35

The additional materials and energy consumed in the manufacturing of EGR equipment were not included as these are not usually recorded. Hence, this is considered a limitation of the study. Furthermore, the installation of EGR has no additional energy or material requirements (Detroit Diesel, 2002).

3. *Integrating utility-connected rooftop solar PV on residential houses*

(Eco-efficiency objective: Reduce material and energy intensity, Maximise sustainable use of renewable resources)

The continuous cost reduction of solar PV technologies in the past 10 years drives the interest of households, communities and corporations in using solar power to lessen their dependence on grid electricity and consequently reduce their energy bills (AEC, 2017). The utilisation of rooftop solar PVs in Australia contributes significantly to reducing GHG emissions at a rate of 200 to 300 Mt CO_2 equivalent per year (Climate Council, 2017). Aside from supplying electricity to a house, a grid-connected solar PV system can also supply surplus electricity back to the grid. The current solar PV system sizes utilised by houses range from 1.5 kW_p to 3 kW_p (AEC, 2017).

In this study, the residential houses were installed with 3.0 kW_p utility-connected rooftop solar PV for self-generation. The deficit electricity requirement was then met by grid electricity generation by the existing hybrid system. Whilst the amount of electricity that can be generated by each household could potentially be influenced by the type of renewable energy technology (e.g. wind, rooftop solar PV, solar thermal), only rooftop solar PV is considered due to its high utilisation across Australia (AEC, 2017). This study also assumed that all the electricity generated is consumed by each household.

The integration of rooftop solar PVs on residential houses has the following considerations.

- This requires the revision of the life cycle inventory due to inclusion of additional energy and materials from the mining to material production of solar PV and BOS, transportation requirements and their eventual disposal. The energy consumption during the installation of rooftop solar PV was not included as this information is not usually recorded, and is thus considered a limitation of this study. The number of houses where rooftop solar PVs will be installed has been discerned according to the hosting capacity limit of each site. The available hosting capacities of Coral Bay and Yungngora in 2017 are 294 kW_p and 413 kW_p, respectively, while Marble Bar has no permissible capacity to host renewable energy for its customers (Horizon Power, 2017).

– In order to estimate the potential reduction of environmental impacts, the analysis has been carried out to include a low installation scenario (25%) and a medium installation (50%) scenario of rooftop solar PVs. The new load demands in Coral Bay and Yungngora have been calculated for the two scenarios using site-specific solar radiation data obtained from BOM (2017) and the technical characteristics of solar PV and BOS. Secondly, the new operational parameters of the hybrid systems including the renewable and diesel power generation and fossil fuel consumption have been estimated using HOMER software. Finally, the inventory for each hybrid system scenario is entered into SimaPro to calculate the environmental impacts.

4. Integrating additional renewable energy capacity

(Eco-efficiency objective: Reduce material and energy intensity, Maximise sustainable use of renewable resources)

High renewable energy penetration in a distribution system has been found to cause voltage fluctuations (Anees, 2012; Karimi et al., 2016; X. Li, Paster, & Stubbins, 2015; Thomson & Infield, 2007). In an intra-hour interval, the distribution system voltage increases at extremely high renewable energy penetration. This unwarranted increase in voltage has adverse effects on household equipment and electronic devices (Tan & Kirschen, 2007). Previous studies have also identified the possibility of feed overload, islanding issues and harmonics as additional constraints to higher renewable energy penetration (Anees, 2012; Karimi et al., 2016).

Karimi et al. (2016) investigated that the distribution system voltage can still be regulated at an intra-hour renewable energy penetration of 50%. Beyond this threshold level, unwarranted voltage rise exists. Similar studies have also found that the nominal system voltage of different distribution systems can be maintained at 40% to 50% renewable energy penetration (NREL, 2003; Thomson & Infield, 2007; Yan & Saha, 2012).

On consultation with Vi Garrood of Horizon Power (personal communication), it was stated that the intra-hour renewable energy penetration in all the hybrid systems is limited to 30% of the transformer nameplate rating. The generation capacity of renewable energy in the hybrid systems can potentially be increased by up to 122%

(371.25 kW_p) in Marble Bar, 9% (75 kW_p) in Coral Bay and 243% (425 kW_p) in Yungngora. The expansion of renewable energy has been considered for the hybrid systems in Marble Bar and Yungngora. However, no expansion was considered for the hybrid system in Coral Bay as the maximum allowable renewable energy capacity has been already reached.

5. ***Integration of all eco-efficiency strategies***

All eco-efficiency strategies were then integrated to estimate the maximum mitigation potential of environmental impacts. The impact assessment results using the combined strategies were then compared with the results obtained from the implementation of individual strategies.

The eco-efficiency strategies were applied in a way that these would not affect the quality and reliability of the power system. Additional inventories for these strategies were generated to conduct a 'follow-up ELCA'. Further analysis on the environmental impacts has been conducted as the change in the inventory could affect the hotspots created (Denham, 2015; Engelbrecht, 2015; K. K. Lawania, 2016). Finally, all the strategies were considered to be implemented in 2017 regardless of the year when the hybrid systems commenced full operation. Based on discussion with Vi Garrood of Horizon Power (personal communication), the remaining years to apply these strategies in Marble Bar, Coral Bay and Yungngora are 15 years, 10 years and 22 years, respectively.

4.3.1 Solar PV–Diesel Hybrid System in Marble Bar

Ten improved RAPS options were generated using individual eco-efficiency strategies and their combinations (Table 4.5). These options have been applied to the solar PV-diesel hybrid system in Marble Bar. The potential environmental impact reduction of each improved RAPS option were estimated (Table 4.6).

Table 4.5 Improved RAPS options for the solar PV-diesel hybrid system in Marble Bar

Improved RAPS Options	Description
MB1	– Reduced load restrictions on diesel engines
MB2	– Integrated exhaust gas recirculation
MB3	– Additional renewable capacity of up to 338 kW_p
MB4	– Additional renewable capacity of up to 450 kW_p
MB5	– Additional renewable capacity of up to 563 kW_p
MB6	– Additional renewable capacity of up to 675 kW_p
MB7	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Additional renewable capacity of up to 338 kW_p
MB8	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Additional renewable capacity of up to 450 kW_p
MB9	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Additional renewable capacity of up to 563 kW_p
MB10	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Additional renewable capacity of up to 675 kW_p

Table 4.6 Environmental impact reduction of all improved RAPS options for the solar PV-diesel hybrid system in Marble Bar (FU = 1 MWh of electricity generation)

Improved RAPS Options	Global Warming Potential (kg CO_2 eq)	Fossil Fuel Depletion (kg Sb eq)	Eutrophication (kg PO_4 eq)	Acidification (kg SO_2 eq)	Photochemical Smog (kg NMVOC)	Ozone Depletion (kg CFC-11 eq)	Respiratory Inorganic (kg $PM_{2.5}$ eq)
MB1	5	0.08	0.01	0.05	0.08	1.4E-6	0.009
MB2	6	0.24	0.21	0.83	1.58	4.2E-6	0.015
MB3	3.3	0.07	0.007	0.04	0.07	1.2E-6	0.006
MB4	13.7	0.25	0.03	0.16	0.27	4.5E-6	0.024
MB5	19.2	0.37	0.04	0.23	0.39	6.5E-6	0.033
MB6	21.2	0.43	0.05	0.27	0.46	7.7E-6	0.036
MB7	14.3	0.36	0.22	0.89	1.68	6.3E-6	0.031
MB8	24.4	0.53	0.23	0.97	1.81	9.2E-6	0.047
MB9	28	0.61	0.24	1.01	1.88	11E-6	0.054
MB10	29.4	0.66	0.24	1.03	1.91	12E-6	0.056

Note: Options highlighted in green provided the largest environmental impacts reduction.

4.3.1.1 Reducing load restrictions on diesel engines (option MB1)

The allowable operating capacity of the diesel engines can be reduced to 10% of its rated capacity to allow the increased penetration of solar power. The decrease in allowable loading capacity of the diesel engines increases solar electricity generation from 12,126 MWh to 12,665 MWh (5% increase) over the operational lifetime. This would reduce diesel electricity generation to 40,475 MWh (1.6% reduction), consumption of diesel to 11,271 m^3 (1.4% reduction) and the transportation of this diesel to 18,804,994 tonnes-km (1.4% reduction).

The resulting environmental benefits of this increased generation of renewable energy were estimated using a follow up ELCA. It was found that this strategy can reduce global warming potential by 1.5%, fossil fuel depletion by 1.6%, eutrophication by 1.49% reduction, acidification by 1.5% reduction, photochemical smog by 1.5% reduction, ozone depletion by 1.6% reduction and respiratory inorganics by 1.5% reduction. The potential environmental impact reduction from this strategy is not particularly promising as it only results in a slight reduction in diesel production and combustion.

4.3.1.2 Integrating exhaust gas recirculation (option MB2)

The diesel engines were retrofitted with EGR to improve the specific fuel consumption and decrease the N_2O emitted during combustion. The results show that there is a reduction in the consumption of diesel to 10,884 m^3 (5% reduction) and transportation of diesel to 18,159,231 tonnes-km (5% reduction) over the plant life. Since an EGR system only affects the specific fuel consumption of the diesel engines, the amount of electricity generated from the solar PV and diesel engines remain at 12,026 MWh and 41,114 MWh, respectively. This means that the diesel engines are producing the same amount electricity with reduced level of fuel consumption.

With the integration of EGR, global warming potential would be reduced by 1.8%, photochemical smog by 31%, ozone depletion by 5%, eutrophication by 31%, acidification by 25% and respiratory inorganics by 2.5%. This not only reduces emissions but also reduces depletion of fossil fuels by 5%. The decrease in the N_2O emission during diesel combustion caused the largest reduction in photochemical smog, eutrophication and acidification. The main reason for this is that N_2O emissions are the biggest contributor to these impacts (Bengtsson & Howard, 2010a; Renouf et al., 2015).

4.3.1.3 Integrating additional renewable energy capacity (options MB3 to MB6)

The existing solar PV capacity in Marble Bar is 304 kW_p. The allowable renewable capacity that is safe from the risk of voltage and frequency variations is 675 kW_p. In order to estimate the increase in renewable energy generated, the analysis includes various installation capacity scenarios of 338 kW_p (option MB3), 450 kW_p (option MB4), 563 kW_p (option MB5) and 675 kW_p (option MB6). Since Marble Bar has high daily average solar radiation, the only renewable capacity installed was solar PV technology. Table 4.7 shows the energy and materials required for solar PV capacity expansion in Marble Bar, which were then incorporated into the LCI for conducting a follow-up ELCA.

Table 4.7 Additional inputs for material production, construction, maintenance and disposal stages of the hybrid system in Marble Bar at different installed solar PV capacity

Material/Energy	Unit	Installed Renewable Energy Capacity			
		338 kW_p (MB3)	450 kW_p (MB4)	563 kW_p (MB5)	675 kW_p (MB6)
Mono-Si PV module	pcs	150	650	1,150	1,650
Concrete	tonnes	45	194	344	494
Steel	tonnes	7	30	54	77
Iron	kg	0	9.2	18.3	27.5
Copper	kg	0	2.2	4.4	6.5
Aluminium	kg	0	4.4	8.7	13
Inverter	pcs	5	22	39	55
Water (solar PV cleaning)	m^3	12	53	93	133
Transportation of equipment to site	tonnes-km	192,618	835,335	1,478,051	2,119,495
Transportation of construction equipment to site	tonnes-km	114,851	114,851	114,851	114,851
Energy consumption of equipment during construction	MJ	16,125	69,876	123,627	177,378

The operational parameters of the hybrid system for each of the installation capacity option were estimated by HOMER. The maximum amount of solar electricity that can be generated with capacities of 338 kW_p, 450 kW_p, 563 kW_p and 675 kW_p over the life cycle has been estimated to be 18,425 MWh, 21,566 MWh, 24,707 MWh and 27,649 MWh, respectively. However, the actual solar power generated has only been estimated to be 12,026 MWh, 12,609 MWh, 14,352 MWh, 15,485 MWh and 16,185 MWh, respectively. These results suggest that the potential solar power is not fully utilised due to the fact that the solar power generated in an intra-hour level may be large enough to supply the demand.

The share of solar power in the energy mix would be increased from 22.6% to 23.7%, 27%, 29% and 30.4%, respectively due to increase in renewable capacity to 338 kW_p, 450 kW_p, 563 kW_p and 675 kW_p. Consequently, almost 1.4% to 10% of diesel consumption and 1.4% to 10% in transporting diesel to generation site is reduced due to this increased share of solar PV generation.

The environmental impacts associated with mining to material production, construction, maintenance and disposal of the installed renewable energy capacity scenarios increased (Table C.8). Whilst the increase in solar PV installation capacity increased environmental impacts during the aforementioned stages, it offers further reduction during the operational stage (Table C.8).

The environmental benefits during the operational stage outweigh the increase of impacts during the mining to material production, construction, maintenance and disposal stages. The overall savings of the hybrid system for all installed capacity scenarios would be between 0.9% and 6% for global warming potential, 1.4% and 8.8% for fossil fuel depletion, 1% and 7% for eutrophication, 1.2% and 8% for acidification, 1.3% and 9% for photochemical smog, 1.4% and 8.8% for ozone depletion and 1% and 5.8% for respiratory inorganics. Further research is important to assess the cost implications of the additional installed renewable energy capacity scenarios.

4.3.1.4 Integration of all eco-efficiency strategies (options MB7 to MB10)

The potential impact reduction in the integration of three strategies could range between 4% and 8.4% for global warming potential, 7% and 13.5% for fossil fuel depletion, 33% and 35% for eutrophication, 26% and 31% for acidification, 33% and 37% for photochemical smog, 7% and 13% for ozone depletion and 5% and 9% for respiratory inorganics.

The improved option MB10 (integration of reduced load restrictions of diesel engines, integration of exhaust gas recirculation and additional renewable energy capacity of up to 675 kW_p) was found to have the highest impact reduction potential of 8.4% for global warming potential, 13.5% for fossil fuel depletion, 35% for eutrophication, 31% for acidification, 37% for photochemical smog, 13% for ozone depletion and 9% for respiratory inorganics. The improved option MB9 (integration of reduced load restrictions on diesel engines, integration of exhaust gas recirculation and additional renewable energy capacity of up to 563 kW_p) is the next best option where its environmental impact reduction ranges from 8% to 35%. Since the operation of diesel engines at lower capacity and the installation of EGR are same across all scenarios, the main variation between these scenarios is dependent on the expansion of renewable energy capacity. Further research on the economic feasibility of the integration of all three strategies is important to determine whether the combined strategies would be more cost-effective than the application of these strategies individually.

4.3.2 Solar PV–Diesel Hybrid System in Yungngora

Nineteen improved RAPS options have been applied to the solar PV-diesel hybrid system in Yungngora using individual eco-efficiency strategies and in combination (Table 4.8). The estimated environmental impact mitigation potential of each option is shown in Table 4.9. These were discussed in the following sections.

Table 4.8 Improved RAPS options for the solar PV-diesel hybrid system in Yungngora

Improved RAPS Options	Description
Yg1	– Reduced load restrictions on diesel engines
Yg2	– Integrated exhaust gas recirculation
Yg3	– Integrated rooftop solar PV on residential houses (105 kW_p)
Yg4	– Integrated rooftop solar PV on residential houses (207 kW_p)
Yg5	– Additional renewable capacity of up to 200 kW_p
Yg6	– Additional renewable capacity of up to 300 kW_p
Yg7	– Additional renewable capacity of up to 400 kW_p
Yg8	– Additional renewable capacity of up to 500 kW_p
Yg9	– Additional renewable capacity of up to 600 kW_p
Yg10	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (105 kW_p)

Improved RAPS Options	Description
	– Additional renewable capacity of up to 200 kW_p
Yg11	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (105 kW_p) – Additional renewable capacity of up to 300 kW_p
Yg12	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (105 kW_p) – Additional renewable capacity of up to 400 kW_p
Yg13	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (105 kW_p) – Additional renewable capacity of up to 500 kW_p
Yg14	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (105 kW_p) – Additional renewable capacity of up to 600 kW_p
Yg15	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (207 kW_p) – Additional renewable capacity of up to 200 kW_p
Yg16	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (207 kW_p) – Additional renewable capacity of up to 300 kW_p
Yg17	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (207 kW_p) – Additional renewable capacity of up to 400 kW_p
Yg18	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (207 kW_p) – Additional renewable capacity of up to 500 kW_p
Yg19	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (207 kW_p) – Additional renewable capacity of up to 600 kW_p

Table 4.9 Environmental impact reduction of all improved RAPS options for the solar PV-diesel hybrid system in Yungngora (FU = 1 MWh of electricity generation)

Improved RAPS Options	Global Warming Potential (kg CO_2 eq)	Fossil Fuel Depletion (kg Sb eq)	Eutrophication (kg PO_4 eq)	Acidification (kg SO_2 eq)	Photochemical Smog (kg NMVOC)	Ozone Depletion (kg CFC-11 eq)	Respiratory Inorganic (kg $PM_{2.5}$ eq)
Yg1	3.3	0.04	0.007	0.03	0.05	0.07E-6	0.006
Yg2	11.3	0.4	0.2	0.91	1.69	0.7E-5	0.02
Yg3	45.2	0.6	0.09	0.44	0.69	1E-5	0.08
Yg4	86.1	1.2	0.16	0.84	1.31	0.21E-5	0.15
Yg5	9.2	0.13	0.02	0.1	0.15	0.23E-5	0.02
Yg6	36.2	0.5	0.07	0.36	0.57	0.9E-5	0.07
Yg7	54.4	0.8	0.1	0.54	0.85	1.4E-5	0.1
Yg8	68.3	1	0.13	0.68	1.06	1.7E-5	0.12
Yg9	78	1.1	0.15	0.77	1.21	2E-5	0.14
Yg10	84.9	1.53	0.37	1.65	2.85	2.7E-5	0.15
Yg11	89.6	1.52	0.32	1.5	2.54	2.6E-5	0.16
Yg12	101.9	1.7	0.34	1.59	2.67	2.9E-5	0.18
Yg13	109.9	1.8	0.35	1.65	2.76	3.1E-5	0.19
Yg14	114.7	1.86	0.36	1.69	2.82	3.3E-5	0.20
Yg15	102.2	1.6	0.34	1.58	2.68	2.8E-5	0.18
Yg16	115.8	1.89	0.36	1.69	2.82	3.3E-5	0.21
Yg17	122.3	1.88	0.37	1.73	2.9	3.3E-5	0.22
Yg18	126.2	1.95	0.37	1.76	2.95	3.4E-5	0.23
Yg19	128.4	1.98	0.37	1.78	2.97	3.5E-5	0.23

Note: Options highlighted in green provided the largest environmental impacts reduction.

4.3.2.1 Reducing load restrictions of diesel engines (option Yg1)

Reducing the permissible operating capacity of the diesel engines could allow higher solar power penetration. The diesel engines in Yungngora can only be run at minimum rated capacity of 20%. Reducing the allowable loading capacity of the diesel engines would increase the solar power generation to 8,558 MWh (4% increase). This would then reduce diesel power generation to 34,817 MWh (1% decrease), diesel consumption to 9,686 m^3 (0.8% decrease) and diesel transportation to 23,543,022 tonnes-km (0.8% decrease).

The environmental benefits of the increased share of renewable energy have been estimated using a follow up ELCA. This option can considerably reduce global warming potential, fossil fuel depletion, eutrophication, acidification, photochemical smog, ozone depletion and respiratory inorganics by 0.9%, 0.8%, 0.94%, 0.92%, 0.96%, 0.82% and 0.96%, respectively. Like Marble Bar, the potential environmental impact reduction from this strategy is minimal.

4.3.2.2 Integrating exhaust gas recirculation (option Yg2)

The integration of EGR in diesel engines can reduce specific fuel consumption and N_2O emissions to air. The simulation results show that diesel consumption over the plant life was reduced to 8,985 MWh (8% reduction) and associated diesel transportation to 21,842,566 tonnes-km (8% reduction). The amount of solar and diesel electricity generation was not affected by the integration of EGR. Electricity generation from these technologies remains at 8,208 MWh and 35,168 MWh, respectively.

The impact assessment results show that all environmental impacts would be reduced. The reduction in eutrophication (32%), photochemical smog (31%) and acidification (26%) were more significant. This can be attributed to large reduction in N_2O emissions, which is the determinant factor for these environmental impacts (Bengtsson & Howard, 2010a; Renouf et al., 2015).

4.3.2.3 *Integrating rooftop solar PV on residential houses (options Yg3 and Yg4)*

The hosting capacity limit of utility-connected rooftop solar PV in Yungngora is 413 kW_p. In this study, installation scenarios of 105 kW_p (option Yg3) and 207 kW_p (option Yg4) have been considered to estimate the reduction in total electricity demand. The energy and materials required in the installation of rooftop solar PVs were incorporated into the LCI for a follow-up ELCA (Table 4.10).

Table 4.10 Additional inputs in the installation of rooftop solar PV on residential houses in Yungngora

Material/Energy	Unit	105 kW_p Installation Scenario (Yg3)	207 kW_p Installation Scenario (Yg 4)
Multi-Si PV module	pcs	408	828
Inverter	pcs	34	69
Transportation of equipment to site	tonnes-km	109,183	221,578

The total amount of solar electricity that can be generated with installation scenarios of 105 kW_p and 207 kW_p have been estimated to be 5,151 MWh and 10,442 MWh, respectively. This reduces the life cycle electricity demand in Yungngora to 38,224 (12% reduction) and 32,934 MWh (24% reduction), respectively.

The new operational parameters of the hybrid system under the two installation scenarios have been estimated using HOMER. The amount of solar power generated over the life cycle has been reduced to 7,576 MWh (8% reduction) and 6,348 MWh (23% reduction), respectively. The amount of electricity generated from the diesel engines has also been reduced to 30,648 MWh (13% reduction) and 24, 585 MWh (24% reduction). The share of solar power in the energy mix increased from 19% to 20% despite the reduction in both solar and diesel power generation.

The environmental impacts associated with the mining to material production and construction of the roof top solar PVs were increased (Table C.9). Despite the additional impacts, the reduction in the total electricity demand reduces the impacts during the operational stage (Table C.9).

An overall environmental benefit was achieved as the savings on operational impact compensated the additional impacts due to the installation of solar PV. Global warming potential was reduced by 12% and 23%, fossil fuel depletion by 12% and 23%, eutrophication by 12% and 23%, acidification by 12% and 24%, photochemical smog by 13% and 24%, ozone depletion by 12%and 24% and respiratory inorganics by 13% and 24% for the 105 kW_p (option Yg3) and 207 kW_p (option Yg4) installation scenarios, respectively. Further research on any economic implications would identify whether this strategy is both environmentally friendly and also cost-effective.

4.3.2.4 Integrating additional renewable energy capacity (options Yg5 to Yg9)

The current solar PV capacity in Yungngora is 175 kW_p. The allowable renewable energy capacity can be increased to a maximum of 600 kW_p without any risk of voltage and frequency fluctuations. In order to estimate the increase in renewable energy generated, various installation capacity scenarios of 200 kW_p (option Yg5), 300 kW_p (option Yg6), 400 kW_p (option Yg7), 500 kW_p (option Yg8) and 600 kW_p (option Yg9) have been included in the analysis. The only RET considered is solar PV given the high solar radiation in Yungngora. Table 4.11 presents the energy and materials required for capacity expansion, which were incorporated into the LCI for a follow up ELCA analysis.

Table 4.11 Additional inputs from material production, construction, maintenance and disposal stages of the hybrid system in Yungngora at different installed solar PV capacity

Material/Energy	Unit	Installed Renewable Energy Capacity				
		200 kW (Yg 5)	300 kW (Yg 6)	400 kW (Yg7)	500 kW (Yg8)	600 kW (Yg9)
Mono-Si PV module	pcs	100	500	900	1300	1700
Concrete	tonnes	65.3	313	561	809	1,057
Steel	tonnes	34.2	164.2	294	424	554
Iron	kg	1,064	5,106	9,149	13,191	17,234
Copper	kg	1.6	8	14	20	26
Aluminium	kg	0.05	0.3	0.5	0.7	0.9
Inverter	pcs	2	8	13	19	25
Water (solar PV cleaning)	m^3	20.3	101.7	183	264.4	345.7
Transportation of equipment to site	tonnes-km	31,413	152,794	273,108	394,489	515,870
Transportation of construction material to site	tonnes-km	9,880	47,423	84,966	122,509	160,052
Transportation of construction equipment to site	tonnes-km	197,602	197,602	197,602	197,602	197,602
Energy consumption for equipment during construction	MJ	4,636	23,178	41,720	60,262	78,805

The operational parameters of the hybrid system for each installation capacity scenario were estimated using HOMER. The maximum amount of solar electricity that can be generated with capacities of 200 kW_p, 300 kW_p, 400 kW_p, 500 kW_p and 600 kW_p over the life cycle have been estimated to be 10,447 MWh, 14,688 MWh 18,930 MWh, 23,172 MWh and 29,089 MWh, respectively. However, only 9,242 MWh, 11,971 MWh, 13,811

MWh, 15,209 MWh and 16,205 MWh, respectively of solar electricity have been generated. This suggests that maximum possible generation is not possible. The main reason for this is that intra-hour electricity generation from solar PV may be large enough to supply demand.

The share of solar power in the energy mix due to increase in capacity to 200 kW_p, 300 kW_p, 400 kW_p, 500 kW_p and 600 kW_p would be increased from 19% to 21%, 28%, 32%, 35% and 37%, respectively. This results in a reduction in diesel consumption by up to 23% and the transportation of diesel by up to 23%. The impact assessment results show that the additional renewable capacity scenarios would increase the environmental impacts caused by the additional inputs from mining to material production construction, maintenance and disposal stages (Table C.10). However, the increase in capacity offers a significant impact reduction during the operational stage (Table C.10).

The savings from the operational stage (downstream stage) were significant enough to offset the additional impacts created by integrating the additional capacities (upstream stage). There would be an overall savings between 3% and 21% for global warming potential, 3% and 22% reduction in fossil fuel depletion, 3% and 21% for eutrophication, 3% and 22% for acidification, 3% and 22% reduction in photochemical smog, 3% and 22% for ozone depletion and 3% and 22% for respiratory inorganics.

4.3.2.5 Integration of all eco-efficiency strategies (options Yg10 to Yg19)

The environmental impact reduction in the use of four strategies could range between 23% and 35% for global warming potential, 30% and 38% for fossil fuel depletion, 53% and 54% for eutrophication, 47% and 51% for acidification, 52% and 55% for photochemical smog, 30% and 39% for ozone depletion and 23% and 36% for respiratory inorganics.

The improved option Yg19 offered the highest impact reduction of 35% for global warming potential, 38% for fossil fuel depletion, 54% for eutrophication, 51% for acidification, 55% for photochemical smog, 39% for ozone depletion and 36% for respiratory inorganics. Since the strategies such as the load restriction of diesel engine operation and the installation of EGR are common to all scenarios, the variations between the scenarios are dependent on the installed rooftop solar PV and the expansion of renewable capacity. More research needs to be done to determine whether the integration of all four strategies would be more cost-effective than the application of these strategies individually.

4.3.3 Wind–Diesel Hybrid System in Coral Bay

Six improved RAPS options have been applied to the hybrid system in Coral Bay using individual eco-efficiency strategies and in combination Table 4.12. The environmental benefits of these options are shown in Table 4.13. Each option was discussed as follows.

Table 4.12 Improved RAPS options for the wind-diesel hybrid system in Coral Bay

Improved RAPS Options	Description
CB1	– Reduced load restrictions on diesel engines
CB2	– Integrated exhaust gas recirculation
CB3	– Integrated rooftop solar PV on residential houses (75 kW_p)
CB4	– Integrated rooftop solar PV on residential houses (147 kW_p)
CB5	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (75 kW_p)
CB6	– Reduced load restrictions on diesel engines – Integrated exhaust gas recirculation – Integrated rooftop solar PV on residential houses (147 kW_p)

Table 4.13 Environmental impact reduction of all improved RAPS options for the wind-diesel hybrid system in Coral Bay (FU = 1 MWh of electricity generation)

Improved RAPS Options	Global Warming Potential (kg CO_2 eq)	Fossil Fuel Depletion (kg Sb eq)	Eutrophication (kg PO_4 eq)	Acidification (kg SO_2 eq)	Photochemical Smog (kg NMVOC)	Ozone Depletion (kg CFC-11 eq)	Respiratory Inorganic (kg $PM_{2.5}$ eq)
CB1	3.3	0.05	0.007	0.04	0.06	0.8E-6	0.007
CB2	4.1	0.16	0.17	0.66	1.3	2.8E-6	0.01
CB3	10.2	0.15	0.02	0.1	0.15	2.6E-6	0.02
CB4	19.8	0.28	0.04	0.2	0.3	5E-6	0.035
CB5	16.6	0.32	0.18	0.75	1.4	5.7E-6	0.034
CB6	26.2	0.45	0.19	0.82	1.5	8E-6	0.05

Note: Options highlighted in green provided the largest environmental impacts reduction.

4.3.3.1 Reducing load restrictions of diesel engines (option CB1)

The permissible operating capacity of the diesel engines can be reduced to 10% of rated capacity to enable higher wind power penetration. The reduction of the allowable operating capacity of the diesel engines increases the life cycle wind electricity generation to 24,200 MWh (1.2% increase). This reduces diesel electricity generation to 41,025 MWh (0.7% reduction), diesel consumption to 11,332 m^3 (0.7% reduction) and diesel transportation to 10,919,312 tonnes-km (0.7% reduction).

A follow-up ELCA has been conducted to estimate the environmental implications of the increase in renewable energy penetration. The impact assessment results show that there is a 1.1%, 1.3%, 1.3%, 1.3%, 1.2%, and 1.3% reduction in global warming potential, eutrophication, acidification, photochemical smog, ozone depletion and respiratory inorganics, respectively. This also has an equivalent 1.2% reduction in fossil fuel depletion. Similar to Marble Bar and Yungngora, this strategy has minimal influence on the potential environmental impact reduction.

4.3.3.2 Integrating exhaust gas recirculation (option CB2)

An EGR is assumed to be installed in the diesel engines to improve specific fuel consumption and decrease N_2O emissions. The simulation results show that the life cycle diesel consumption is reduced to 10,951.17 MWh (4% reduction) and the diesel transportation to 10,551,950 tonnes-km (4% reduction). Both diesel and wind electricity generation remain at 41,318 MWh and 23,907 MWh respectively, as these operational parameters were not affected by the strategy.

The follow-up ELCA results show that environmental impacts would be reduced. The greatest impact reduction was found for eutrophication (31%) followed by photochemical smog (31%) and acidification (24%). This was attributed to the significant decrease in N_2O emissions during combustion, which accounted for these environmental impacts (Bengtsson & Howard, 2010a; Renouf et al., 2015).

4.3.3.3 *Integrating rooftop solar PV on residential houses (options CB3 and CB4)*

The allowable hosting capacity to maintain the quality of RAPS is 293 kW_p. In order to estimate the reduction in the total electricity demand, the study has been carried out to include installation scenarios 75 kW_p (option CB3) and 147 kW_p (option CB4). The energy and materials required in the installation of rooftop solar PV on residential houses are shown in Table 4.14.

Table 4.14 Additional inputs in the installation of rooftop solar PV on residential houses in Coral Bay

Material/Energy	Unit	75 kW_p Installation Scenario (CB3)	147 kW_p Installation Scenario (CB4)
Multi-Si PV module	pcs	300	588
Inverter	pcs	25	49
Transportation of equipment to site	tonnes-km	80,282	157,352

The amount of solar electricity that can be generated with installation scenarios of 25% and 50% over the remaining life cycle has been estimated to be 1,862 MWh and 3,646 MWh, respectively. This reduces the life cycle electricity demand in Coral Bay by 3% and 6%, respectively.

The operational parameters of the hybrid system for the installation scenarios have been estimated using HOMER. The amount of wind electricity generation with installation scenarios of 25% and 50% over the life cycle has been reduced to 23,620 MWh (1.2% reduction) and 23,276 MWh (3% reduction), respectively. Whereas the amount of electricity generated from diesel engines has been reduced to 39,743 MWh (5% reduction) and 38,302 MWh (7% reduction), respectively. Although the wind electricity generation was reduced, the share of renewable in the energy mix increased. This is due to the fact that the reduction rate of diesel electricity generation is higher than for wind electricity generation. Consequently, diesel consumption is reduced by up to 7% and diesel transportation by up to 7% due to the reduction in diesel electricity generation.

The impacts associated with the additional energy and materials from the rooftop solar PV were increased, but it offered a reduction during the operational stage (Table C.11). The impact savings during the operational stage offset the additional impacts due to installation of solar PVs. It was found that the overall environmental impacts savings for the 75 kW_p (option CB3) and 147 kW_p (option CB4) installation scenarios would be reduced by 3% and 7% for global warming potential, 4% and 7% for fossil fuel depletion, 3% and 7% for eutrophication, 4% and 7% for acidification, 4% and 7% for photochemical smog, 4% and 7% for ozone depletion and 4% and 7% for respiratory inorganics.

Despite the low solar radiation in Coral Bay, the installed rooftop solar PV reduced the environmental impacts. The economic implications of this strategy require further analysis to determine as to whether the installation of solar PV on residential houses is a cost-effective strategy.

4.3.3.4 Integration of all eco-efficiency strategies (options CB5 and CB6)

The combination of three strategies has more environmental benefits. The potential environmental impact reduction for global warming potential is between 6% and 9%, fossil fuel depletion between 8% and 11%, eutrophication between 34% and 36%, acidification is between 28% and 30%, photochemical smog is between 34% and 36%, ozone depletion is between 8% and 11% and respiratory inorganics is between 7% and 10%. Since the strategies including diesel engine load restriction and EGR installation are the same in both scenarios, the main factor that affects the reduction of impacts is the installation of solar PVs on residential houses.

Further research could assess whether the integration of all three strategies would be more cost-effective than the application of these strategies individually.

4.3.4 Summary of Eco-Efficiency Strategies Implementation for RAPS in Western Australia

This study analysed the environmental implications of a number of eco-efficiency strategies for improving the environmental performance of the RAPS systems. The main findings from this study are now summarised.

1. Lowering the load restriction of the diesel engine below 30% of the rated capacity was found to increase the penetration of renewable energy in the mix in all RAPS systems

(options MB1, Yg1 and CB1). This decreased the amount of electricity generated from the diesel engines and hence reduced all environmental impacts by up to 2%.

2. The diesel engines equipped with EGR (options MB2, Yg2 and CB2) was found to be the most effective strategy in reducing photochemical smog, eutrophication and acidification by up to 30%.

3. The installation of rooftop solar PV on residential houses was found to reduce the life cycle electricity demand in Coral Bay and Yungngora by 6% and 24%, respectively. Reduction of environmental impacts during the operational stage outhweighs the environmental impacts associated with the incorporation of the rooftop solar PV components. This option was not implemented in Marble Bar since the power supply system has no hosting capacity available.

4. Reduction of environmental impacts during the operational stage due to renewable capacity expansion (e.g. improved options MB3 to MB6 – integration of additional solar PV capacity of up to 675 kW_p in Marble Bar) outweighs the environmental impacts associated with the mining and manufacturing production, installation and maintenance of the solar PV system components into the RAPS system .

5. The combination of eco-efficiency strategies offers more environmental benefit than considering individual strategies for implementation. The improved options MB10 (integration of reduced load restriction on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 675 kW_p), Yg 19 (integration of reduced load restriction on diesel engines, integrated exhaust gas recirculation, installed rooftop solar PV of 207 kW_p and additional renewable capacity of up to 60 kW_p), and CB6 (integration of reduced load restriction on diesel engines, integrated exhaust gas recirculation, installed rooftop solar PV of 147 kW_p) offer the largest environmental impact savings for the RAPS system in Marble Bar (Table 4.6), Yungngora (Table 4.9) and Coral Bay (Table 4.13).

Further investigation into the economic benefits of the improved RAPS options is required for a comprehensive evaluation of eco-efficient RAPS options. Section 4.5 discusses the cost-effectiveness of the improved RAPS options using LCC tool as part of the EEA framework.

4.4 Step 3: Life Cycle Costing (LCC) of Existing and Improved RAPS Options

This section applies the LCC tool to estimate the life cycle costs of the existing and improved RAPS options as a part of the EEA framework. The inputs used in the LCI of the ELCA were considered for this LCC in order to maintain consistency between environmental and economic analyses. All site-specific cost information was sourced from Horizon Power as much as possible in order to conduct a realistic economic analysis. The cost elements used in the LCC of the hybrid systems are detailed in Appendix D (Table D.1).

The engineering cost estimation method was used to estimate the capital costs (diesel engines, solar PV system, BOS, transport and construction) and the operation and maintenance costs (diesel power production, routine maintenance of diesel engines and spare parts replacement) of the hybrid systems. When information was not available for each case study site, analogous cost estimation method was used to estimate other costs (acquisition cost of wind turbine generators and flywheel energy storage, routine maintenance of renewable technologies) (BREE, 2013; CO2CRC et al., 2015; Rossow, 2003). The costs associated with the feasibility studies (market study, legislative factors and power station design), project management, support services (corporate management, administrative overheads, insurances and taxes), dismantling and disposal were excluded from this LCC analysis.

The diesel prices were directly obtained from Recharge Petroleum and Refuels Australia. The change in diesel prices in the future is a significant consideration in conducting an LCC. However, this study does not consider this change due to uncertainty in future diesel prices (Ally & Pryor, 2016).

Specific considerations of the LCC of the improved RAPS options are listed as follows.

- It was assumed that the improvement of the load restriction in the diesel engines during the operational stage did not incur additional cost.
- The price of retrofitting EGR valves for the diesel engines was estimated using available retail market prices.
- The lifespan of the EGR equipment was assumed to have the same lifespan as the diesel engines. Therefore, no replacement was considered.

- Based on industry specifications and published literature, the lifespans of both rooftop solar PVs and extended capacities have been considered as 25 years, (Fu et al., 2015; Hong et al., 2016; Sunpower, 2008; Suntech Power, 2014). Therefore, no replacement was considered for the remaining life cycle of the hybrid systems.

4.4.1 Solar PV-Diesel Hybrid System in Marble Bar

4.4.1.1 Life cycle costing of existing RAPS system

The life cycle cost of the solar PV-diesel hybrid system in Marble Bar was found to be 174 AUD per MWh. The operation and maintenance cost (125 AUD per MWh, 72%) accounts for the largest share of the total cost followed by the capital cost (49 AUD per MWh, 28%). The breakdown of the capital cost and the operation and maintenance costs are shown in Appendix D (Table D.2 and Table D.3).

The cost of diesel has been identified as an economic hotspot (95%) during the operation and maintenance stage. The costs of solar PV and BOS maintenance, diesel engine maintenance and flywheel energy storage maintenance were found to contribute only 2.1%, 2% and 0.7%, respectively. Diesel cost also accounts for the largest portion (69%) of the life cycle cost and hence identified as an 'economic hotspot'. Petrillo et al. (2016) also observed that the operational stage (diesel fuel cost) contributes the largest share (53%) in the overall life cycle cost of a hybrid system. Whilst the share of solar electricity in the energy mix (23%) is high, the high cost of diesel outweighs the benefits associated with the use of solar PV.

4.4.1.2 Life cycle costing of improved RAPS options

The life cycle cost savings of the ten improved RAPS options are shown in Table 4.15. These were discussed in the following sections.

Table 4.15 Life cycle cost savings of all improved RAPS options for the solar PV-diesel hybrid system in Marble Bar (FU = 1 MWh of electricity generation)

Improved RAPS Options	Description	Life Cycle Cost (AUD)
MB1	Reduced load restrictions on diesel engines	2.6
MB2	Integrated exhaust gas recirculation	8.1
MB3	Additional renewable capacity of up to 338 kW_p	0.3
MB4	Additional renewable capacity of up to 450 kW_p	0.5
MB5	Additional renewable capacity of up to 563 kW_p	-2.3
MB6	Additional renewable capacity of up to 675 kW_p	-6.3
MB7	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 338 kW_p	10.8
MB8	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 450 kW_p	10.2
MB9	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 563 kW_p	6.6
MB10	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 675 kW_p	2.2

Note: Options highlighted in green provided the largest life cycle cost savings, while options highlighted in orange increased the life cycle cost.

Economic analysis of reducing load restrictions on diesel engines (option MB1)

The breakdown of the operation and maintenance cost of reducing the load restrictions on diesel engine operation is presented in Appendix D (Table D.4). The integration of this option was found to have a life cycle cost saving of 2.6 AUD per MWh (0.6% reduction). This reduction in life cycle cost is mainly attributed to the cost reductions associated with diesel power production and routine maintenance of diesel engines. This strategy was found not only to reduce environmental impacts but also to reduce the associated cost in operating diesel engines (ARENA, 2014; Meyer, 2015).

Economic analysis of integrating exhaust gas recirculation (option MB2)

The breakdown of the capital cost and the operation and maintenance cost of integrating EGR is presented in Appendix D (Table D.4). This strategy was found to have an overall economic benefit of 8 AUD per MWh (2% reduction) as the operation and maintenance cost savings outweigh the cost of manufacturing and installing EGR.

Economic analysis of integrating additional renewable energy capacity (options MB3 to MB6)

The present value of capital cost increases with the expansion of RETs as additional costs are associated with the purchase of additional PV panels and BOS, the transportation of additional equipment to the construction site and installation charges including the costs associated with labour, tools and machinery. This analysis considers the expansion of solar PV capacity from 304 kW_p to 338 kW_p (option MB3), 450 kW_p (option MB4), 563 kW_p (option MB5) and 675 kW_p (option MB6).

The breakdown of the capital cost is presented in Appendix D (Table D.4). The additional cost of integrating additional solar PV capacity varies from 99,133 AUD (option MB3) to a maximum of 1,128,430 AUD (option MB6). This translates into the increase between 2% and 19% in the capital cost of the existing RAPS system, respectively.

The increase in solar PV capacity has an influence on the net present value of the operation and maintenance cost (Table D.4). The routine maintenance of the additional solar PV system was found to have an additional cost that varies between 0.16 AUD and 1.8 AUD per MWh, while the reduction in diesel engine operation and maintenance was found to have a cost saving between 2.3 AUD and 17 AUD per MWh. The cost savings from the diesel engine operation compensate the cost of maintaining the solar PV system, which result in an overall operation and maintenance cost savings between 2.1 AUD per MWh (0.7% reduction) and 15.2 AUD per MWh (5% reduction).

The improved option MB5 (additional renewable capacity of up to 450 kW_p) offers an overall savings of 0.5 AUD per MWh (0.1% reduction) followed by IRE338 with savings of 0.3 AUD per MWh (0.06% reduction) (Table 4.16). The options IRE563 and IRE675 were found to have an overall increase in the life cycle cost by 2.3 AUD per MWh (0.6%) and 6.3 AUD per MWh (1.5%), respectively. This is because of the fact that the capital cost is large that it outweighs the operational cost savings (Table 4.16). These results infer that an environmentally advantageous option may not always be economically attractive, but this can be considered eco-efficient when the sustainability pillars environment and economics were treated with the same importance using eco-efficiency portfolio analysis (Arceo et al., 2017; Kicherer et al., 2007; Saling et al., 2002). Chapter 5 thus investigates this issue further.

Table 4.16 Cost associated with integrating additional renewable energy capacity and equivalent cost savings (FU = 1 MWh of electricity generation)

Improved RAPS Option	Additional Cost in Integrating Renewable Energy Capacity (AUD)	Cost Savings Due to Additional Renewable Energy Generation (AUD)
MB3	1.8	2.1
MB4	8.1	8.6
MB5	15	12.7
MB6	21.5	15.2

Economic analysis of the integration of all eco-efficiency strategies (options MB7 to MB10)

The breakdown of the capital cost and the operation and maintenance cost of integrating three eco-efficiency strategies is presented in Appendix D (Table D.4). The improved option MB7 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 338 kW_p) offered the largest life cycle cost savings of 10.8 AUD per MWh (2.57% reduction) (Table 4.15).

The inclusion of a diesel engine load restriction and the integration of exhaust gas recirculation to all additional solar PV capacity scenarios were found to improve the economic viability of options MB5 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 563 kW_p) and MB6 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 675 kW_p) (Table 4.15).

4.4.2 Solar PV-Diesel Hybrid System in Yungngora

4.4.2.1 Life cycle costing of existing RAPS system

The breakdown of the capital cost and the operation and maintenance cost of the solar PV-diesel hybrid system in Yungngora is shown in Appendix D (Table D.5 and Table D.6). The life cycle cost was found to be 178 AUD per MWh of electricity generation. The operation and maintenance cost (146 AUD per MWh, 82%) has the largest contribution to the total life cycle cost followed by the capital cost (32 AUD per MWh, 18%).

The cost associated with diesel power generation accounted for 96% of the operation and maintenance cost and 79% of the total life cycle cost. The main reason for this is due to the high cost of diesel despite a considerable share (9%) of solar electricity in the energy mix. Similar to Marble Bar, the operation and maintenance cost was identified as an economic hotspot.

4.4.2.2 Life cycle costing of improved RAPS options

The life cycle cost savings of nineteen improved RAPS options are shown in Table 4.17. These were discussed in the following sections.

Economic analysis of reducing load restrictions of diesel engines (option Yg1)

The breakdown of the operation and maintenance cost of improving the load restriction of the diesel engine operation is presented in Appendix D (Table D.7). This strategy was found to have life cycle cost savings of 1.3 AUD per MWh (0.6% reduction). This decrease is attributed to the cost reduction associated with the reduction of diesel consumption as well as the routine maintenance of diesel engines.

Economic analysis of integrating exhaust gas recirculation (option Yg2)

The breakdown of the capital cost and the operation and maintenance cost of integrating EGR is presented in Appendix D (Table D.7). This strategy was found to have an overall economic benefit of 10.3 AUD per MWh (4.5% reduction) as the operation and maintenance cost savings outweigh the cost of manufacturing and installation the EGR components.

Table 4.17 Life cycle cost savings of all improved RAPS options for the solar PV-diesel hybrid system in Yungngora (FU = 1 MWh of electricity generation)

Improved RAPS Options	Description	Life Cycle Cost (AUD)
Yg1	Reduced load restrictions on diesel engines	1.3
Yg2	Integrated exhaust gas recirculation	10.3
Yg3	Integrated rooftop solar PV on houses (105 kW_p)	1.4
Yg4	Integrated rooftop solar PV on houses (207 kW_p)	0.6
Yg5	Additional renewable capacity of up to 200 kW_p	1.7
Yg6	Additional renewable capacity of up to 300 kW_p	4
Yg7	Additional renewable capacity of up to 400 kW_p	3.9
Yg8	Additional renewable capacity of up to 500 kW_p	1.6
Yg9	Additional renewable capacity of up to 600 kW_p	-2.6
Yg10	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (105 kW_p) and additional renewable capacity of up to 200 kW_p	17
Yg11	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (105 kW_p) and additional renewable capacity of up to 300 kW_p	16.6
Yg12	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (105 kW_p) and additional renewable capacity of up to 400 kW_p	13.7
Yg13	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (105 kW_p) and additional renewable capacity of up to 500 kW_p	8.8
Yg14	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (105 kW_p) and additional renewable capacity of up to 600 kW_p	2.7
Yg15	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (207 kW_p) and additional renewable capacity of up to 200 kW_p	9.5
Yg16	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (207 kW_p) and additional renewable capacity of up to 300 kW_p	6.5
Yg17	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (207 kW_p) and additional renewable capacity of up to 400 kW_p	2.1
Yg18	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (207 kW_p) and additional renewable capacity of up to 500 kW_p	-4.2
Yg19	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (207 kW_p) and additional renewable capacity of up to 600 kW_p	-11

Note: Options highlighted in green provided the largest life cycle cost savings, while options highlighted in orange increased the life cycle cost.

Economic analysis of integrating rooftop solar PVs on residential houses (options Yg3 and Yg4)

The present value of capital cost increased with the installation of solar PVs on residential houses. This analysis considers installation scenarios of 105 kW_p (option Yg3) and 207 kW_p (option Yg4). The breakdown of the capital cost is presented in Appendix D (Table D.7). The results show that the additional costs of integrating rooftop solar PVs are 775,323 AUD (18% increase) for the 25% installation scenario (RSPV25) and 1,573,428 AUD (36% increase) for the 50% installation scenario (RSPV50).

The installed capacity of solar PVs was also found to affect the operation and maintenance cost (Table D.7). The equivalent cost savings was found to be between 19 AUD per MWh (10% reduction) and 37 AUD per MWh (20% reduction), respectively.

The operation and maintenance cost savings from this option outweigh the capital cost (Table 4.18). The options RSPV25 and RSPV50 were found to have an overall cost savings of 1.4 AUD per MWh (0.6% reduction) and 0.6 AUD per MWh (0.3% reduction), respectively.

Table 4.18 Cost associated with integrating rooftop solar PVs and equivalent cost savings (FU = 1 MWh of electricity generation)

Improved RAPS Option	Additional Cost in Integrating Rooftop Solar PVs (AUD)	Equivalent Cost Savings (AUD)
Yg3	17.6	19
Yg4	36.4	37

Economic analysis of integrating additional renewable energy capacity (options Yg 5 to Yg9)

The present value of capital cost increases with solar PV capacity expansion as there is an additional costs associated with the purchase of additional PV panels, the transportation of additional equipment to the construction site and installation charges of these items including labour, tools and machinery. This analysis considers the expansion of renewable energy capacity from 175 kW_p to 200 kW_p (option Yg5), 300 kW_p (option Yg6), 400 kW_p (option Yg7), 500 kW_p (option Yg8) and 600 kW_p (option Yg9). The breakdown of capital cost is presented in Appendix D (Table D.7). The additional cost of integrating additional renewable energy capacity varies between 91,479 AUD (2% increase in capital cost) and 1,369,905 AUD (32% increase).

The capacity expansion also has an influence on the present value of the operation and maintenance cost (Table D.7). The routine maintenance of the additional solar PV system was found to have an additional cost that varies between 0.1 AUD and 2 AUD per MWh, while the reduction in diesel engine operation and maintenance was found to have cost savings between 3.9 AUD and 31 AUD per MWh. The cost savings from the diesel engine operation compensate the cost of maintaining the solar PV system, which result in an overall operation and maintenance cost savings between 3.8 AUD per MWh (2% reduction in operation and maintenance cost) to 29 AUD per MWh (15.5% reduction).

The improved option Yg6 (additional renewable capacity of up to 300 kW_p) offers an overall savings of 4 AUD per MWh (1.8% reduction) followed by Yg7, Yg5 and Yg8 with overall cost savings of 3.9, 1.7 and 1.5 AUD per MWh, respectively (Table 4.19). The option Yg9 (additional renewable capacity of up to 600 kW_p) was found to have an overall increase in the life cycle cost by 2.6 AUD per MWh (1.1%) (Table 4.19). The main reason for this is due to the high capital cost that outweighs the operational cost savings. These findings suggest that an environmentally friendly option may incur additional cost, but may be found to be eco-efficient (Arceo et al., 2017; Kicherer et al., 2007; Saling et al., 2002).

Table 4.19 Cost associated with integrating additional renewable energy capacity and equivalent cost savings (FU = 1 MWh of electricity generation)

Improved RAPS Option	Additional Cost in Integrating Renewable Energy Capacity (AUD)	Cost Savings Due to Additional Renewable Energy Generation (AUD)
Yg5	2.3	3.8
Yg6	9.7	13.7
Yg7	16.6	20.5
Yg8	24	25.6
Yg9	31.5	29

Economic analysis of the integration of all eco-efficiency strategies (options Yg10 to Yg 19)

The breakdown of the capital cost and the operation and maintenance cost of the integrated eco-efficiency strategies (options Yg10 to Yg19) is presented in Appendix D (Table D.7). The improved option Yg15 (reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (207 kW_p) and additional renewable capacity of up to 200 kW_p) offers the highest cost savings at 17 AUD per MWh (Table 4.17). The options Yg18 (reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (207 kW_p) and additional renewable capacity of up to 500 kW_p) and Yg 19 (reduced load restrictions on diesel engines, integrated exhaust gas recirculation, integrated rooftop solar PV on houses (207 kW_p) and additional renewable capacity of up to 600 kW_p) with higher rooftop solar PV installation and renewable capacity expansion would increase the life cycle cost between 4.2 AUD per MWh and 11 AUD per MWh (Table 4.17). These findings infer that higher renewable penetration may not necessarily be cost-effective, but an investigation has been carried out in Chapter 5 to identify whether these options are eco-efficient.

4.4.3 Wind-Diesel Hybrid System in Coral Bay

4.4.3.1 Life cycle costing of existing RAPS system

The breakdown of capital cost and operation and maintenance costs of the hybrid wind-diesel system in Coral Bay are presented in Appendix D (Table D.8 and Table D.9). The life cycle cost was found to be 192 AUD per MWh of electricity generation. The operation and maintenance cost was found to contribute 68% (130 AUD per MWh) to the life cycle cost followed by the capital cost at 32% (62 AUD per MWh).

The cost of diesel power production accounted for 93% of the operation and maintenance cost and 63% of the overall life cycle cost. The maintenance of wind generators, diesel engines and flywheel energy storage accounted for only 4.4%, 2% and 0.5% of the total operation and maintenance cost, respectively. Despite high wind penetration, the high cost of diesel outweighs the benefit associated with the use of wind generators.

Similar to the findings of the hybrid systems in Marble Bar and Yungngora and the life cycle cost investigation conducted by Petrillo et al. (2016), the diesel power generation cost during the operation and maintenance stage was found to be an economic hotspot.

4.4.3.2 Life cycle costing of improved RAPS options

The life cycle cost savings of the six improved RAPS options are shown in Table 4.20. Each option was discussed as follows.

Table 4.20 Life cycle cost savings of all improved RAPS options for the wind-diesel hybrid system in Coral Bay (FU = 1 MWh of electricity generation)

Improved RAPS Options	Description	Life Cycle Cost (AUD)
CB1	Reduced load restrictions on diesel engines	1.3
CB2	Integrated exhaust gas recirculation	7.43
CB3	Integrated rooftop solar PV on houses (75 kW_p)	-2
CB4	Integrated rooftop solar PV on houses (147 kW_p)	-4.3
CB5	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation and integrated rooftop solar PV on houses (75 kW_p)	5.3
CB6	Reduced load restrictions on diesel engines, integrated exhaust gas recirculation and integrated rooftop solar PV on houses (147 kW_p)	2.7

Note: Options highlighted in green provided the largest life cycle cost savings, while options highlighted in orange increased the life cycle cost.

Economic analysis of reducing load restrictions of diesel engines (option CB1)

The breakdown of the operation and maintenance cost due to the incorporation of load restriction on the diesel engines is shown in Appendix D (Table D.10). This strategy was found to reduce the life cycle cost by 1.3 AUD per MWh (0.4%), which is mainly due to the reduction in diesel power generation and associated routine maintenance of diesel engines. Similar to the other hybrid systems, this strategy was found not only to reduce environmental impacts but also to reduce the associated cost in operating the diesel engines (ARENA, 2014; Meyer, 2015).

Economic analysis of integrating exhaust gas recirculation (option CB2)

The breakdown of both the capital cost and the operation and maintenance cost changes due to the integration of EGR (Table D.10). This option was found to have the largest cost savings of 7.7 AUD per MWh (Table 4.20) as the savings from the operation and maintenance compensate the cost of integrating the EGR.

Economic analysis of integrating rooftop solar PVs on residential houses (options CB3 and CB4)

The present value of capital cost increases with the installation of solar PVs. This analysis considers installation scenarios of 75 kW_p (option CB3) and 147 kW_p (option CB4). The breakdown of the capital cost is presented in Appendix D (Table D.10). The additional costs of integrating rooftop solar PVs were estimated to be 559,791 AUD (5.3% increase in capital cost) and 1,096,919 AUD (10.5% increase), respectively.

The installed solar PVs have influence on the present value of the operation and maintenance cost (Table D.10). The installation scenarios 75 kW_p and 147 kW_p would have an equivalent cost savings between 6.6 AUD per MWh (2% reduction) and 12.6 AUD per MWh (3.7% reduction), respectively.

Unlike Yungngora, these options were found to increase the life cycle cost as the cost savings from the operation and maintenance were not large enough to offset the costs of installing rooftop solar PVs. The installation scenarios of 75 kW_p (option CB3) and 147 kW_p (option CB4) were found to increase the life cycle cost by 2 AUD per MWh (0.4%) and 4.3 AUD per MWh (0.9%), respectively (Table 4.21). These results can be attributed to the low solar radiation in Coral Bay. Although these options have increased the life cycle cost, it needs to be investigated as to whether these are eco-efficient options (Arceo et al., 2017; Kicherer et al., 2007; Saling et al., 2002).

Table 4.21 Cost associated with integrating rooftop solar PVs and equivalent cost savings (FU = 1 MWh of electricity generation)

Improved RAPS Option	Additional Cost in Integrating Rooftop Solar PVs (AUD)	Equivalent Cost Savings (AUD)
CB3	8.6	6.6
CB4	16.9	12.6

Economic analysis of the integration of all eco-efficiency strategies (options CB5 and CB6)

The breakdown of the capital cost and the operation and maintenance cost of the integrated eco-efficiency strategies is presented in the Appendix D (Table D.10). The inclusion of diesel engine load restriction, the integration of exhaust gas recirculation and the increase in rooftop solar PV installation capacities were found to be economically viable. The results show that both options offer cost savings of 2.3 AUD per MWh (0.5% reduction) and 5.3 AUD per MWh (1% reduction).

4.4.4 Discussion

This chapter has identified potential eco-efficiency strategies for implementation with renewable-diesel hybrid systems in Western Australia. Since most studies have only compared the environmental benefits of using a hybrid system over a conventional power supply (Perera, Attalage, Perera, & Dassanayake, 2013; Schofield, 2011; Smith et al., 2015), this study is the first of its kind to use eco-efficiency strategies to improve the environmental performance of a hybrid system without entailing excessive costs. Each hybrid system requires an individual analysis to determine more environmentally and economically effective strategies due to differences in available renewable energy resources, climatic conditions, location and load use pattern.

The installed capacity of the existing RET influenced the potential capacity expansion. The installed wind capacity in Coral Bay is already set to the maximum level, while the installed solar PV capacity in Marble Bar and Yungngora can be expanded up to 675 kW_p and 600 kW_p respectively without compromising the reliability of the system. Whilst this capacity expansion could result to environmental benefits, there are additional costs at higher installed capacity.

The allowable hosting capacity limit of rooftop solar PVs on residential houses also influenced the potential environmental impact reduction. Marble Bar has no available capacity left to accommodate rooftop solar PVs, while Coral Bay and Yungngora have 294 kW_p and 413 kW_p, respectively. Whilst the installation of residential solar PVs could result in environmental benefits, there is a possibility that the life cycle cost could increase at locations with low solar radiation.

The technical specification of the diesel engines also has an influence on the potential impact reduction. The diesel engines in Marble Bar and Coral Bay can be operated at a minimum of 10% of rated capacity, while the diesel engines in Yungngora can be operated by up to 20% of rated capacity. The reduction in environmental impact due to increased penetration of renewables in the energy mix is higher at lower operating capacity.

4.5 Conclusion

This chapter presented the implementation of eco-efficiency strategies to treat the environmental hotspots of hybrid RAPS systems in Western Australia. The EEA framework tools including environmental life cycle assessment (ELCA) and life cycle costing (LCC) were used to evaluate the potential environmental impact and economic implications of the existing and improved RAPS options. It was found that that the environmental and economic implications of these options vary with the type of the hybrid systems due to differences in diesel engine specification, existing renewable energy capacity and allowable rooftop solar PV hosting capacity.

No single option in all hybrid systems offered the highest environmental impact reduction with the largest life cycle cost savings potential. This chapter has shown that some options are more environmentally friendly but offer less cost savings or have increased the cost. For instance, improving the load restriction of the diesel engines, integrating exhaust gas recirculation and expanding the solar PV capacity to 675 kW_p in Marble Bar offer the largest environmental impact reduction but increased the life cycle cost. In contrast, some options have less environmental benefit but offered the largest reduction in the life cycle cost. This is exemplified when the RAPS system in Yungngora has an improved load restriction on diesel engines, an integrated exhaust gas recirculation, installed rooftop solar PV on residential houses and an expanded solar PV capacity of 200 $kW_{p.}$ These findings suggest that ELCA and LCC analyses alone cannot assist in the selection of eco-efficient RAPS options.

An eco-efficiency portfolio analysis can help select an option that reflects the balance between environment and economics. In eco-efficiency analysis, the environment and economic pillars of sustainability were treated with equivalence (Arceo et al., 2017; Kicherer et al., 2007; Saling et al., 2002). This has been addressed in Chapter 5 using a *'portfolio analysis'* to select the most eco-efficient option for the solar PV-diesel hybrid systems in Marble Bar and Yungngora and for the wind-diesel hybrid system in Coral Bay.

Chapter 5

Eco-Efficiency Analysis for Remote Area Power Supply in Western Australia

5.1 Introduction

This chapter presents the use of portfolio analysis to address research Objective 5, which aims to assess the eco-efficiency of the improved RAPS options as part of the EEA framework. The eco-efficiency performance of the options is assessed by synergising the trade-off between the results from the environmental life cycle assessment (ELCA) and life cycle costing (LCC) in Chapter 4. A portfolio is generated to assist in the comprehensive visualisation and selection of an eco-efficient RAPS option.

This investigation focuses mainly on the identification of the most eco-efficient RAPS option for each hybrid system in Western Australia. The portfolio that was generated by using an EEA framework in this chapter has been discussed as follows.

- The impact assessment results in the existing and improved RAPS options were normalised, weighted and aggregated in units of equivalent inhabitants using equations 3.4 and 3.5. Both significant environmental impacts (photochemical smog, ozone depletion, eutrophication, acidification, respiratory inorganics, fossil fuel depletion and global warming potential) and relatively less significant impacts (mineral depletion, land use and ecological diversity, water depletion, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, ionising radiation and human toxicity) were normalised and weighted in order to obtain a single score in terms of equivalent inhabitants.

- The life cycle costs of both existing and improved RAPS options were also normalised in terms of equivalent inhabitants using equation 3.6.

- Portfolio analysis has been conducted by comparing the portfolio position of the existing and improved RAPS options (Figure 3.13). Eco-efficient options are located above the eco-efficiency line (area shaded in green), wherein the most eco-efficient option has the largest perpendicular distance above this line. Less favourable RAPS options are located below the eco-efficiency line (area shaded in red).

- Sensitivity analysis confirms how changes in input data and methodological approaches influence the results of the portfolio analysis (Saling et al., 2002). The following variables has been considered for this analysis.

  1. A sensitivity analysis was conducted to assess the effect of economic discount rates and diesel prices in the selection of eco-efficient options. The economic discount rates influence the future costs of power production, thus affecting the total life cycle cost of different strategies (Kannan et al., 2006; Marszal et al., 2012). On the other hand, a large diesel price will increase the operational cost of power production and vice versa (Kannan et al., 2006; Marszal et al., 2012). The discount rates of power generating technologies are not well documented, and there is uncertainty in future diesel price data. For this study, both parameters were assumed to be increased and decreased by 20% of the nominal values.

  2. The effect of carbon tax has also been investigated as studies suggest that this could affect the operational cost of electricity producers (Kneifel, 2010; Marron, Toder, & Austin, 2015). A large carbon tax will disincentivise the production of electricity from fossil fueled generators. The price of carbon tax is expected to increase from the tax that was first set in Australia and there is no consensus in literature on what tax would best reflect its price . A 38 AUD/tonne of CO_2 , obtained from Hunt (2015) has conservatively been assumed in the present study.

A substantial interpretation of the results in this eco-efficiency analysis is important for assisting in the decision-making process and for disseminating results to a general audience (Kicherer et al., 2007; Saling, 2016; Saling et al., 2002). Each of the hybrid systems was discussed individually to formulate separate conclusions and recommendations for the power distribution utility (Horizon Power). The results can assist in policy planning and investments to reduce the contribution of RAPS systems to environmental impacts in a cost-effective manner.

5.2 Step 4: Eco-Efficiency Portfolio Analysis

5.2.1 Portfolio Results for the Solar PV-Diesel Hybrid System in Marble Bar

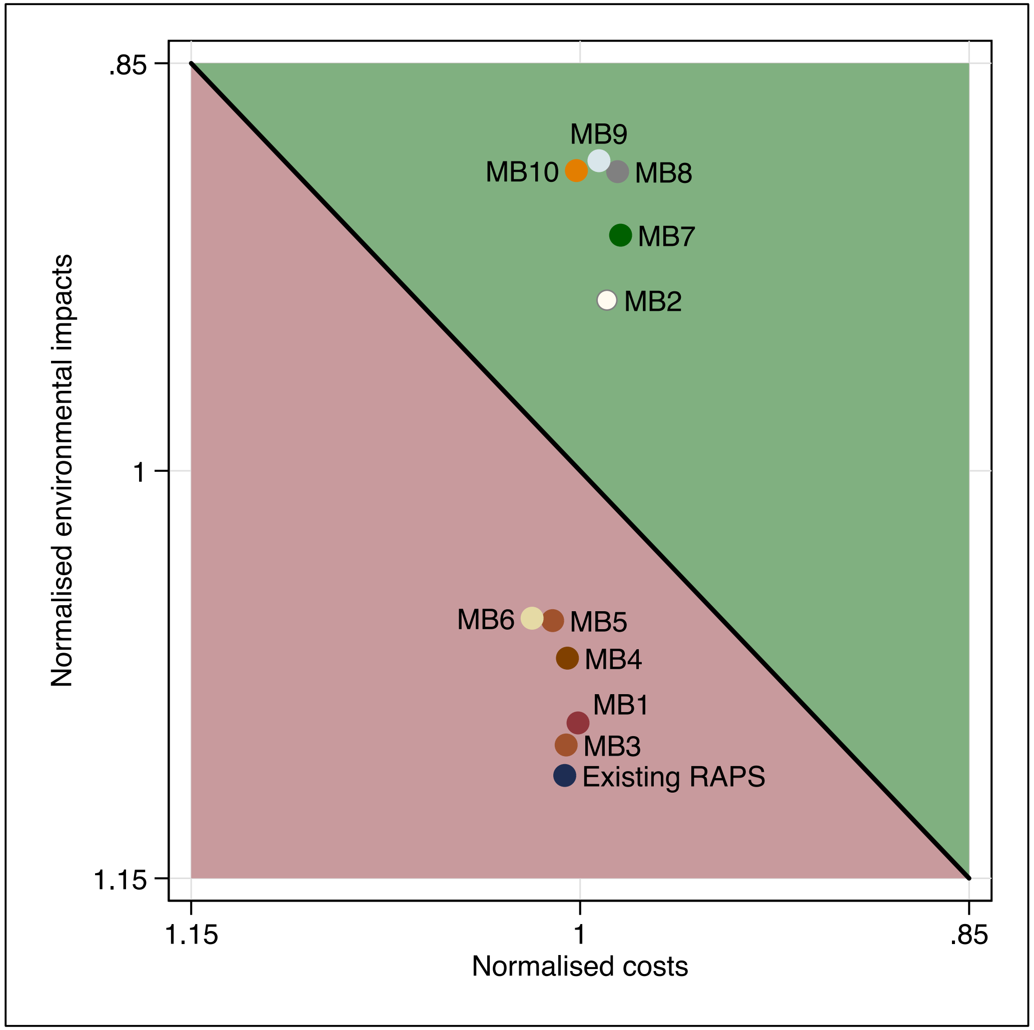
A RAPS system with reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 450 kW_p (option MB8) is the most eco-efficient option (Figure 5.1, Table E.1). This option is more eco-efficient than the most environmentally friendly option (MB10) due to higher cost saving (2%) that outweighs the small amount of environmental impact reduction (0.4%). Similarly, this option is more eco-efficient than the most cost-effective option (MB7) due to higher impact reduction (2%) that offsets the low cost reduction (0.1%).

A sensitivity analysis has been conducted to determine the effect of discount rates, diesel prices and carbon tax in the selection of options for improving the eco-efficiency of the hybrid system in Marble Bar.

Sensitivity of the eco-efficiency portfolio to discount rates and diesel prices

The change in both discount rates and diesel prices influences the eco-efficiency performance of the eco-efficient options. The 20% increase in discount rate would increase the eco-efficiency performance between 1.2% and 5.6%, while the 20% decrease would reduce the performance between 2% and 5.5% (Table E.2). The 20% increase in diesel prices would increase the eco-efficiency performance between 1.8% and 8%, while the 20% decrease would reduce this between 1.3% and 6.8% (Table E.3).

The analysis shows that the sensitiveness of the eco-efficient options to discount rates and diesel prices is low. The reason for this can be attributed to the low sensitiveness of the life cycle cost of each option to discount rates and diesel prices. This analysis also shows that option MB8 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 450 kW_p) remains the most eco-efficient option.



Legend

- MB1 – reduced load restrictions on diesel engines
- MB2 – integrated exhaust gas recirculation
- MB3 – additional renewable capacity of up to 338 kW_p
- MB4 – additional renewable capacity of up to 450 kW_p
- MB5 – additional renewable capacity of up to 563 kW_p
- MB6 – additional renewable capacity of up to 675 kW_p
- MB7 – reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 338 kW_p
- MB8 – reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 450 kW_p
- MB9 – reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 563kW_p
- MB10 – reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 563kW_p

Figure 5.1 Portfolio of the existing and improved RAPS options in Marble Bar

Sensitivity of the eco-efficiency portfolio to carbon tax

The imposition of carbon tax has an influence on the eco-efficiency performance of the improved RAPS options. The performance of these options would be increased between 1% and 5% (Table E.4). However, the analysis shows that the improved RAPS options are not sensitive to carbon tax. This can be attributed to the low sensitiveness of the life cycle cost of each option to carbon tax. The sensitivity analysis also shows that the most eco-efficient RAPS option remained to be improved option MB8 (reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 450 kW_p).

5.2.2 Portfolio Results for the Solar PV-Diesel Hybrid System in Yungngora

Yungngora RAPS system with reduced load restrictions on diesel engines, integrated exhaust gas recirculation, installed rooftop solar PVs on residential houses (207 kW_p) and additional renewable capacity of up to 400 kW_p (option Yg17) provides the most eco-efficient RAPS option (Figure 5.2, Table E.5). This option is more eco-efficient than the most economically attractive option (Yg10) as the higher environmental impact reduction (20%) outweighs losses associated with low cost saving (6.6%). This option is also more eco-efficient than the most environmentally friendly option (Yg19) due to higher cost savings that compensates the disadvantages associated with the low level of environmental impact reduction (2%)

The improved options Yg18 and Yg19, which have increased life cycle costs were also found as eco-efficient options (Figure 5.2). This is due to the high environmental impact reduction (41.7% and 42.2%) that outweighs the increasd life cycle cost (1.8% and 5%).

A sensitivity analysis has been conducted to determine the effect of change in discount rates, diesel prices and carbon tax in the selection of strategies to improve the eco-efficiency performance of the hybrid system in Yungngora.

Sensitivity of the eco-efficiency portfolio to discount rates and diesel prices

The variation in both discount rates and diesel prices affects the eco-efficiency performance of the improved RAPS options. The 20% increase in discount rate would vary the eco-efficiency performance between -15% and 3%, while a 20% decrease would also result in the variation of eco-efficiency performance between -6% and 21% (Table E.6). In the case of diesel price, a 20% increase would vary the eco-efficiency performance between -1.8% and 16%, while a 20% decrease would vary the performance between -15% and 2% (Table E.7).

Whilst the eco-efficiency performance of the improved RAPS options varies under different discount rates and diesel prices, option Yg17 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation, installed rooftop solar PVs on residential houses (207 kW_p) and additional renewable capacity of up to 400 kW_p) remains the most eco-efficient option.

Sensitivity of the eco-efficiency portfolio to carbon tax

The imposition of carbon tax was found to influence the eco-efficiency performance of the improved RAPS options. Similar to the previous analysis, the results would vary between -7 and 1.5 (Table E.8). Although the eco-efficiency performance varies, the analysis shows that the improved RAPS options are not sensitive to carbon tax. This can be attributed to the low sensitivity of the life cycle cost each option to carbon tax. The improved option Yg17 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation, installed rooftop solar PVs on residential houses (207 kW_p) and additional renewable capacity of up to 400 kW_p) is still the most eco-efficient option before and after the imposition of carbon tax.

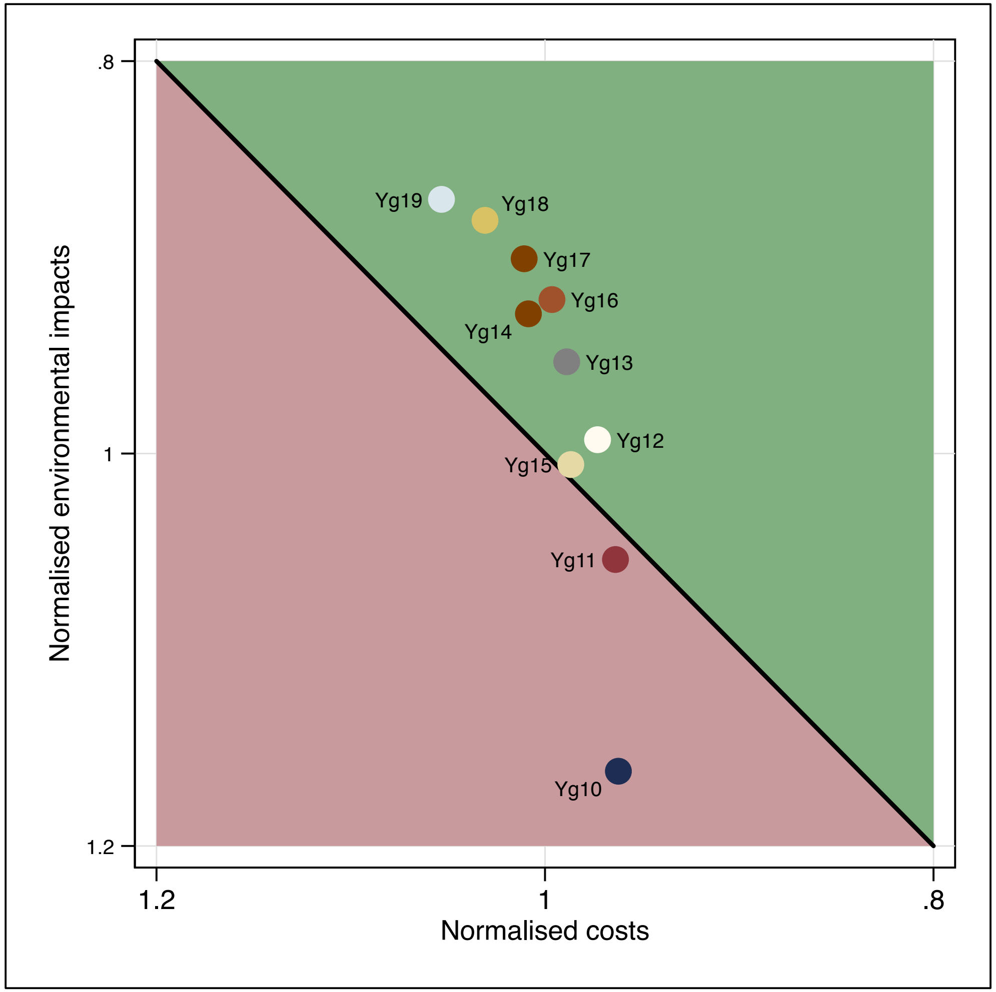


Figure 5.2 Portfolio of the existing and improved RAPS options in Yungngora (Note: Improved options with poor eco-efficiency are not shown.)

Legend

- Yg10 – reduced load restrictions (LR) on diesel engines, integrated exhaust gas recirculation (EGR), integrated rooftop solar PV (RSPV) (105 kW_p) and additional renewable capacity of up to 200 kW_p
- Yg11 – reduced LR on diesel engines, integrated EGR, integrated RSPV (105 kW_p) and additional renewable capacity of up to 300 kW_p
- Yg12 – reduced LR on diesel engines, integrated EGR, integrated RSPV (105 kW_p) and additional renewable capacity of up to 400 kW_p
- Yg13 – reduced LR on diesel engines, integrated EGR, integrated RSPV (105 kW_p) and additional renewable capacity of up to 500 kW_p
- Yg14 – reduced LR on diesel engines, integrated EGR, integrated RSPV (105 kW_p) and additional renewable capacity of up to 600 kW_p
- Yg15 – reduced LR on diesel engines, integrated EGR, integrated RSPV (207 kW_p) and additional renewable capacity of up to 200 kW_p
- Yg16 – reduced LR on diesel engines, integrated EGR, integrated RSPV (207 kW_p) and additional renewable capacity of up to 300 kW_p
- Yg17 – reduced LR on diesel engines, integrated EGR, integrated RSPV (207 kW_p) and additional renewable capacity of up to 400 kW_p
- Yg18 – reduced LR on diesel engines, integrated EGR, integrated RSPV (207 kW_p) and additional renewable capacity of up to 500 kW_p
- Yg19 – reduced LR on diesel engines, integrated EGR, integrated RSPV (207 kW_p) and additional renewable capacity of up to 600 kW_p

5.2.3 Portfolio Results for the Wind-Diesel Hybrid System in Coral Bay

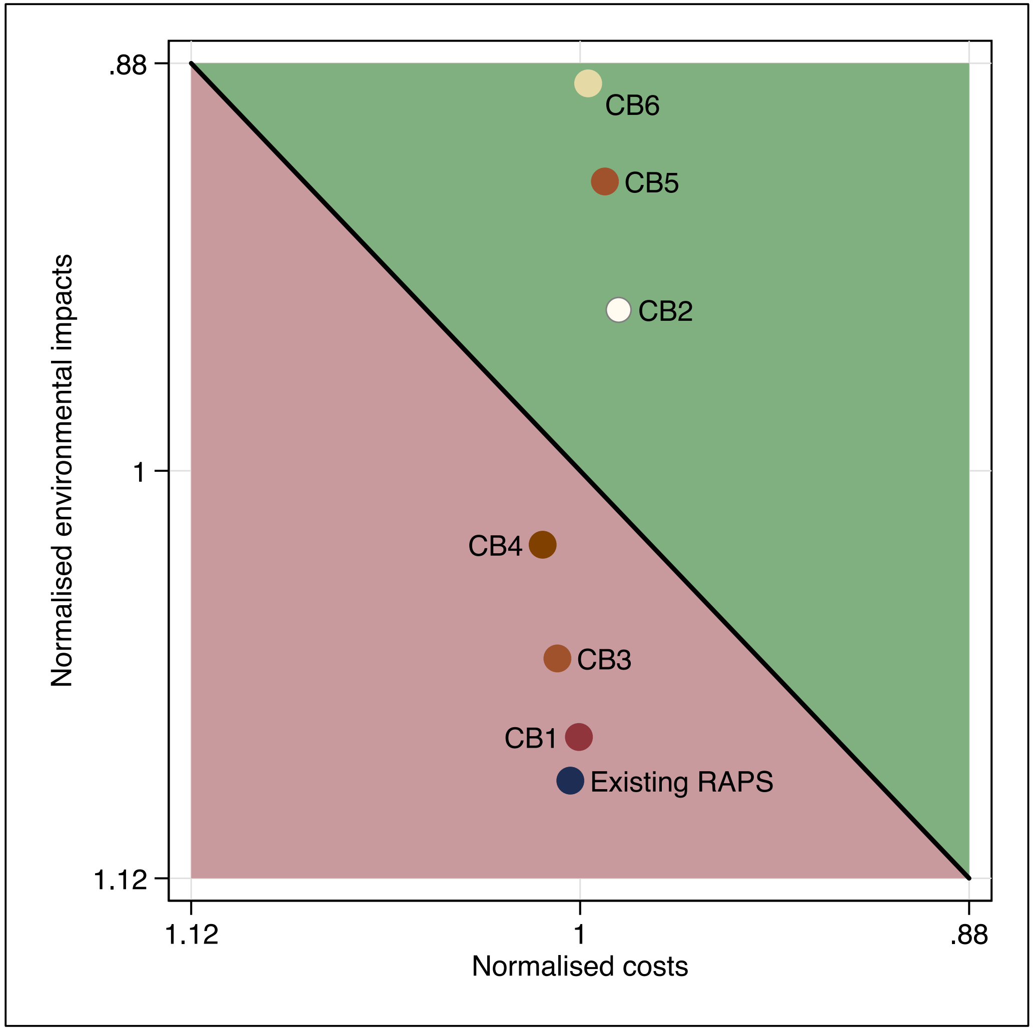
A RAPS system with reduced load restrictions on diesel engines, integrated exhaust gas recirculation and installed rooftop solar PVs on residential houses (207 kW_p) (option CB6) is not only the most environmentally friendly option but also the most eco-efficient option for Coral Bay (Figure 5.3, Table E.9). Whilst the cost saving of this strategy is slightly lower than the most cost-effective option CB2 (integrated exhaust gas recirculation), this option is more eco-efficient due to higher level of environmental impact reduction (8%).

A sensitivity analysis has been conducted to determine the effect of discount rates, diesel prices and carbon tax in the selection of eco-efficient options for the hybrid system in Coral Bay.

Sensitivity of the eco-efficiency portfolio to discount rates and diesel prices

The variation in both discount rates and diesel prices influences the eco-efficiency performance of the improved RAPS options. The 20% increase in discount rate would increase the eco-efficiency performance between 4% and 6%, while the 20% decrease would reduce this performance between 4% and 6% (Table E.10). The 20% increase in diesel price would increase the performance between 2.6% and 7%, while the 20% decrease would reduce this performance between 2% and 6% (Table E.11).

The results show that the improved RAPS options are not sensitive to discount rates and diesel prices. The reason for this is due to the fact that the life cycle cost of each option is not sensitive to discount rates and diesel prices. The analysis also shows that the most eco-efficient option is still option CB6 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation and installed rooftop solar PVs on residential houses (207 kW_p)).



Legend

- CB1 – reduced load restrictions on diesel engines
- CB2 – integrated exhaust gas recirculation
- CB3 – integrated rooftop solar PV (75 kW_p)
- CB4 – integrated rooftop solar PV (147 kW_p)
- CB5 – reduced load restrictions on diesel engines, integrated exhaust gas recirculation and integrated rooftop solar PV (75 kW_p)
- CB6 – reduced load restrictions on diesel engines, integrated exhaust gas recirculation and integrated rooftop solar PV (147 kW_p)

Figure 5.3 Portfolio of the existing and improved RAPS options in Coral Bay

Sensitivity of the eco-efficiency portfolio to carbon tax

Carbon tax influences the eco-efficiency performance of the improved RAPS options. The results show that eco-efficiency could be decreased between 0.1% and 2% due to a carbon tax of 38 AUD/tonne of CO_2 emitted (Table E.12). This infers that the sensitiveness of the improved RAPS options to carbon tax is low and the most eco-efficient option is still option CB6 with or without the imposition of the tax.

5.3 Discussions

The portfolio analysis has identified eco-efficient options for each hybrid system in Western Australia. This also provides an overview of the environmental and economic implications of each strategy to power distribution utilities. The key findings derived from this chapter are summarised as follows.

Eco-efficient options vary with hybrid systems

The results show that there is no single option that provides the best solution. The options MB7 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 450 kW_p), Yg17 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation, installed rooftop solar PVs on residential houses (207 kW_p) and additional renewable capacity of up to 400 kW_p) and CB6 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation and installed rooftop solar PVs on residential houses (207 kW_p)) were found to be the most eco-efficient option for Marble Bar, Coral Bay and Yungngora, respectively. Despite the differences in the recommended option, the integration of all strategies can provide the maximum possible eco-efficiency performance.

As discussed in 4.6, the differences in the selection of an eco-efficient RAPS option is due to the differences in the maximum allowable renewable energy capacity, the allowable hosting capacity limit of rooftop solar PV on residential houses, the technical specifications of the diesel engines, resource availability, climatic conditions and load use patterns.

Eco-efficiency analysis assists in the optimisation of renewable energy capacity

The portfolio analysis can be used for optimising the installed renewable energy capacity that would offer the most eco-efficient supply of electricity (Arceo et al., 2017). For the hybrid system in Marble Bar, the option MB8 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 450 kW_p) that has less capacity expansion has been found to be more eco-efficient than the more environmentally beneficial options MB9 and MB10 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation and additional renewable capacity of up to 563/675 kW_p) (Figure 5.1). Similar finding has been observed for the hybrid system in Yungngora (Figure 5.3). These findings contradict the widely accepted belief that high renewable energy capacity would be a better option, but in an eco-efficiency point of view, the environmental benefit must be integrated with the incurred cost associated with the additional capacity.

Environmentally friendly options that increased the life cycle cost can still be eco-efficient

This study has shown that an environmentally friendly option that has an additional cost can still be eco-efficient. For example, the options Yg18 and Yg19 (integration of reduced load restrictions on diesel engines, integrated exhaust gas recirculation, installed rooftop solar PVs on residential houses (207 kW_p) and additional renewable capacity of up to 500/600 kW_p) for the hybrid system in Yungngora were found as eco-efficient options despite the additional cost incurred. This is attributed to the large environmental impact reduction of 41.7% and 42.2% that compensates the costs increased by only 2% and 5%, respectively. These results support similar research findings obtained by Arceo et al. (2017).

Eco-efficiency analysis assists in strategic decision-making for policy implementation

The portfolio analysis will enable energy planners, policymakers and researchers to develop policies to achieve eco-efficient RAPS options. Through this analysis, it was proved that carbon tax would not be an effective policy to improve the eco-efficiency of RAPS systems.

A scenario analysis where the government would subsidize the capital cost for integrating additional renewable energy capacity in the hybrid system of Marble Bar is shown in Figure 5.4. It appears that the integration of additional capacity up to 675 kW_p, which is ranked second in the initial analysis has emerged as the most eco-efficient option if the government's financial support has been provided. This implies that portfolio analysis can help envision the implications of future policy changes on the eco-efficiency performance of RAPS systems.

5.4 Conclusion

This chapter compared the eco-efficiency performance of both existing and improved RAPS options using portfolio analysis to determine an eco-efficient option. This study has identified that the performance of eco-efficient options would vary with hybrid systems. However, the integration of all strategies including the improvement of diesel engine load restriction, the integration of exhaust gas recirculation, the integration of rooftop solar PV on residential houses and the integration of additional renewable energy capacity would offer the highest eco-efficiency performance.

This research has also highlighted that an eco-efficient option not necessarily have to be both environmentally friendly and economically feasible. The potential environmental impact reduction could potentially offset any additional cost in order to be considered an eco-efficient RAPS option.

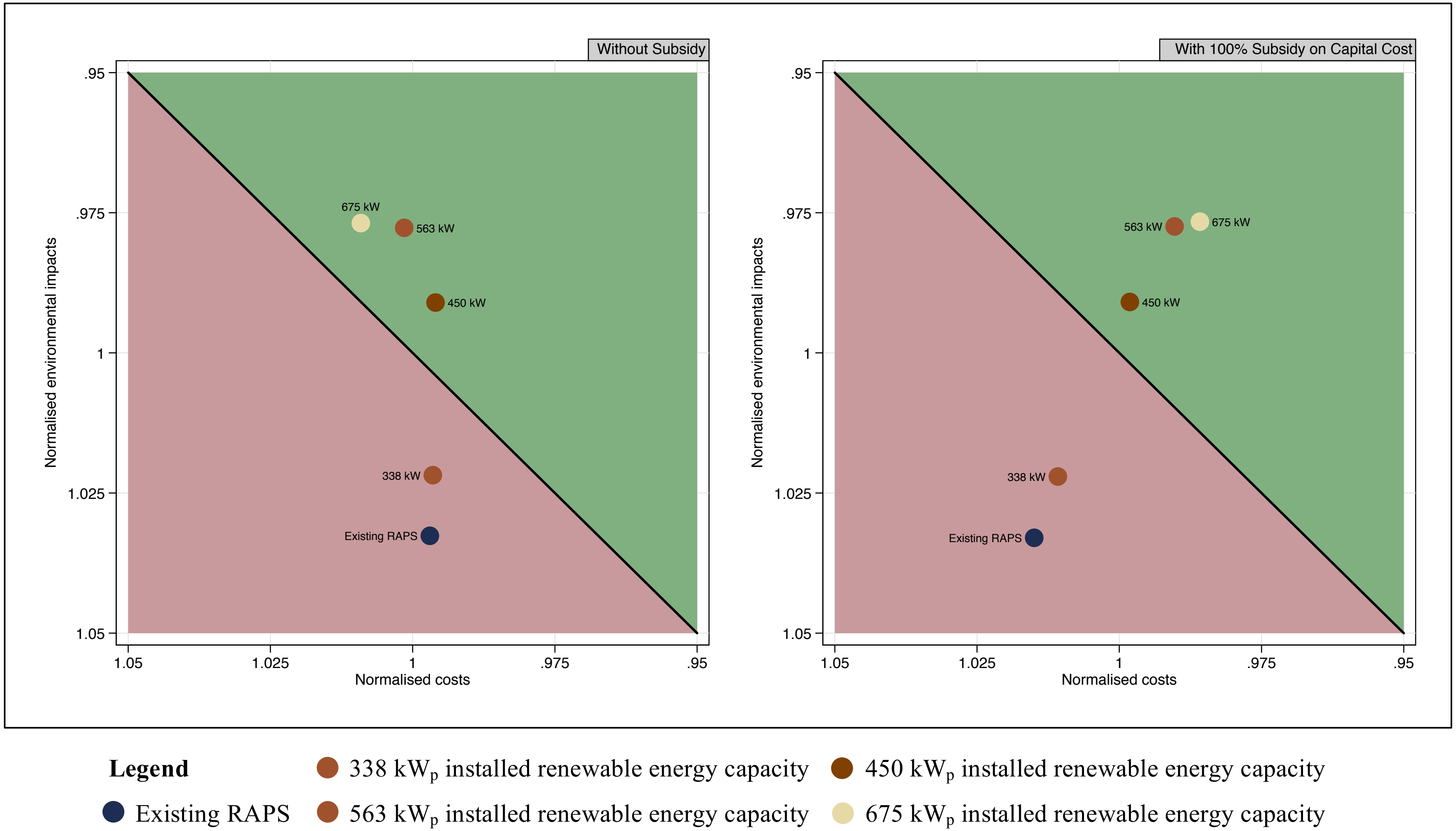


Figure 5.4 Scenario analysis on providing 100% subsidy on capital cost of additional renewable energy capacity for the hybrid system in Marble Bar

Chapter 6
Conclusion

Hybridisation of the traditionally used diesel generating systems with renewable energy technologies for remote area power supply helps in achieving the goals of sustainable energy. These hybrid energy systems bring environmental benefits through the mitigation of the emission of greenhouse gases and air particulates. The operational costs are also reduced since renewable electricity generation offsets the use of diesel for electricity generation. Previous research and actual renewable-fossil fuel energy systems have highlighted that hybridisation demonstrates eco-efficiency. No research so far has been developed for assessing potential eco-efficiency improvement of remote hybrid energy systems.

Eco-efficiency of remote hybrid energy systems in Western Australia includes not only reducing the emission intensive electricity generation but also the application of cost-effective strategies. In this research, eco-efficiency analysis (EEA) framework was developed through rigorous review of literature in the area of sustainable energy, renewable energy and remote area power supply. This framework contributes in the development of region specific eco-efficient options for various power supply systems. Eco-efficiency strategies such as reduced diesel engine load restriction, exhaust gas recirculation, utility connected rooftop solar PVs and maximised installed renewable energy capacity demonstrated environmental impact and cost savings potential to these hybrid energy systems.

In Western Australia, the application of eco-efficiency strategies varies due to differences in geographic conditions, load use patterns and system technical specifications. A number of challenges were found that prevent the implementation of eco-efficiency options in these remote hybrid energy systems. These challenges are discussed as follows.

- Research is being conducted on improving the load performance of diesel engines to allow higher penetration of renewable energy generation.

- Research to date is still determining solutions to prevent voltage and frequency fluctuations at high renewable energy penetration in a power distribution system.

- The utilisation of rooftop PVs on residential houses could increase the system life cycle cost if available solar radiation is low.

- Further research on the use of concentrated solar power in remote areas of Western Australia will help determine whether this technology can be more beneficial than PV technologies.

- Personal communication with Horizon Power stated that the primary function of energy storage systems in the remote hybrid energy systems of Western Australia is for power quality support and grid balancing (length of discharge is only for a couple of hours). Research is being conducted to determine the application of large scale energy storage system for energy management (length of discharge can last for days).

The potential improvement and limitations of this research are specified as recommendations for future research. Some of these recommendations include the following.

- The ELCA part of the framework should be extended to include recycling and remanufacturing of RAPS components as previous studies have identified environmental credits that can be received from these end-of-life strategies (Demir & Taşkın, 2013; Guezuraga et al., 2012; Smith et al., 2015)

- The EEA framework only considers the economic and environmental pillars of sustainability. Future research can enhance the model by incorporating social life cycle assessment (SLCA) to assess the social implications of the eco-efficient RAPS options.

- Policy changes (e.g. renewable portfolio standards) in RAPS are important for consideration in the EEA framework to determine their implications on the eco-efficiency performance. This research has found that a policy such as the imposition of carbon tax slightly influence the eco-efficiency performance of the existing and improved RAPS options.

- The renewable energy technologies (RETs) used for RAPS are rapidly evolving. For example, new RETs such as wave and tidal energy may be widely used in the near future. Therefore, the EEA framework is recommended to be used in determining the eco-efficiency performance of these new and emerging technologies.

- The normalisation factors used in the environmental life cycle assessment and life cycle costing parts of this research were not region specific values since no data is available. Future studies can conduct the determination of normalisation factors both at regional and state levels in Australia. The framework developed in this thesis has the flexibility to incorporate region specific normalisation factors to estimate the environmental and economic values to perfectly represent the regional situation. A sensitivity analysis by varying the weights of the economic and environmental objectives in the final portfolio analysis can be considered in the future research.

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Appendix A

Clean Techn Environ Policy
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ORIGINAL PAPER

Eco-efficiency analysis for remote area power supply selection in Western Australia

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Abstract Remote area power supply (RAPS) systems in Western Australia account for more than 56% of total off-grid electricity supply in Australia and utilise carbon emission intensive diesel and gas generating technologies for power supply. Most of these RAPS systems are run by environmentally unfriendly conventional fuel due to economic reasons. An eco-efficiency analysis (EEA) framework was therefore developed to explore the environmental and economic efficiency of the current diesel RAPS systems in Western Australia. ISO 14040:2006 for Life Cycle Assessment and AS/NZS 4536:1000 (R2014) for Life Cycle Costing have been used to estimate the associated environmental impacts and costs of RAPS systems in conducting an EEA. The results show that the integration of solar photovoltaic panels and an energy storage system into existing diesel generating units for power supply could improve the eco-efficiency of the existing system. It was found that a 4% increase in total life cycle costs with the use of a hybrid system could potentially decrease the overall environmental impacts by 16%.

Keywords Remote area power supply system · Eco-efficiency indicators · Life cycle assessment · Life cycle costing

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Introduction

Globally, more than 1.3 billion people live in remote areas without access to electricity (International Energy Agency 2012). Remote area power supply (RAPS) systems have been utilised to provide electricity to areas without access to centralised grids. Most RAPS systems are largely situated in developing countries, but some can be found in developed countries. In Australia, these systems account for 6% of Australia's electricity demand for only 2% of Australian inhabitants (Australian Renewable Energy Agency 2014). These systems predominantly supply electricity for agricultural and mining industries, and off-grid communities (Evans and Peck 2011).

The worldwide off-grid installed diesel generator capacity was at 23 GW in 2012 (International Renewable Energy Agency 2015). The widespread utilisation of diesel for RAPS is due to its reliability and availability across Australia. In Australia, almost 99% of energy for RAPS is sourced from emission intensive diesel fuels. This not only causes additional greenhouse gas (GHG) emissions due to the combustion and transportation of the fuels but also used scarce oil resources (Petrillo et al. 2016). The expansion of mining towns in Western Australia associated with the rapid exploration of minerals and petroleum could further increase this demand (Department of Mines and Petroleum 2015).

Renewable energy technologies (RETs) have been proven to offer significant environmental benefits for off-grid power supply (Allan et al. 2015). A 100% renewable energy uptake for off-grid areas is a challenging task due to economic and technical constraints (i.e. reliability) associated with the generation of power from these new technologies. The diversification of energy sources with diesel generators and RETs could address these economic and technical challenges (Holtmeyer et al. 2013).

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These hybrid systems can supply dispatchable electricity by maximising the use of renewable energy whilst having diesel generators as a backup supply system. These systems not only provide reliable power supply but also reduce the amount of diesel required for electricity generation (Schofield 2011). In Western Australia, many off-grid power distribution utilities still favour the use of diesel power stations. These utilities do not consider the environmental benefits associated with the integration of RETs into RAPS system due to their high initial capital costs (McHenry 2009). Energy planning is therefore required to identify methods for reducing associated impacts with RAPS systems whilst generating electricity economically. Eco-efficiency is a sustainability assessment tool that can help achieve this objective.

The eco-efficiency of off-grid power supply has mainly been assessed using a life cycle assessment (LCA) approach, where the functional use of technologies has been expressed in terms of environmental impact (Verfaillie and Bidwell 2000). These LCA studies have various goals, including the comparison of environmental performance between diesel and renewable energy and conventional power supplies for microgrid (Smith et al. 2015), off-grid residential use (Fleck and Huot 2009), off-grid power supply networks (Schofield 2011), stand-alone mobile house (Sevencan and Çiftcioğlu 2013), desalination plants (Shahabi et al. 2014) and stand-alone communication systems (Petrillo et al. 2016). LCA studies have also been presented for assessing the associated impacts of specific power supply technologies including standby diesel generators (Benton et al. 2017), offshore wind farms (Huang et al. 2017), onshore wind farms (Demir et al. 2013), multi-crystalline solar panels (Chen et al. 2016), mono-crystalline solar panels (Hou et al. 2016) and thin film solar panels (Kim et al. 2014). The environmental impacts used for comparative analysis of technologies generally include impact categories relating to ecosystem, human health and natural resources (Smith et al. 2015). However, previous eco-efficiency assessment of a RAPS system has not considered the link between economic viability and environmental benefits.

An eco-efficiency analysis (EEA) methodology has been developed by Saling et al. (2002) for comparative analysis of product alternatives. This involves measuring both life cycle costs and environmental impacts for a defined functional use. The method assumes that economic and environmental implications are equally important for comparative sustainability assessment (Saling 2016). A number of studies have followed this conceptual framework in order to compare alternative options to come up with sustainable decision-making strategy (Uhlman and Saling 2010). The concept of eco-efficiency, however, has not been considered for assessing the cost-effectiveness of environmentally friendly off-grid power supply options.

This study has endeavoured to develop an EEA framework to assist in the selection of appropriate RAPS options. To achieve this objective, a diesel power supply option and a hybrid power supply option have been selected for a remote area in the Pilbara region of Western Australia. The relevant impact categories for RAPS have been estimated using SimaPro software. The analysis of cost impacts were based on the life cycle costing method developed for Australia and New Zealand (Standards Australia/Standards New Zealand 2014). Finally, both environmental impacts and life cycle costs of the alternative options have been used to determine the more eco-efficient option.

Materials and methods

An eco-efficiency analysis framework (Fig. 1) was developed using the principles of life cycle perspective following the established eco-efficiency concept of Saling et al. (2002) and Kicherer et al. (2007). This integrates environmental life cycle assessment (ELCA), life cycle costing (LCC) and finally eco-efficiency assessment (EEA). The tasks that were performed to apply the EEA framework to meet the objectives were described in the following sections.

Life cycle assessment

Environmental life cycle assessment of RAPS systems

The environmental life cycle assessment (ELCA) of two RAPS systems has been conducted using an ISO 14040-44 guideline (ISO 2006). ELCA is the compilation of the inputs and outputs, and the evaluation of potential environmental impacts of a product system throughout its life cycle. This approach includes four steps: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation.

The goal of the ELCA was to estimate environmental impacts during the entire life cycle of the RAPS systems. The functional unit of the systems has been determined as one MWh of electricity generation. The power plant is required to generate 2125 MWh of electricity per year for 25 years. Figure 2 shows the upstream and downstream stages of the entire life cycle of a diesel system. Upstream stages include the extraction of raw materials, manufacturing of equipment, delivery of equipment to the site and finally the construction of the plant. The downstream stages include power production, maintenance of the power supply system and end-of-life disposal of the equipment. All the inputs and outputs of these stages were calculated for the functional unit, and the environmental impacts were then estimated.

Fifteen environmental impact categories have been considered as relevant for assessing the environmental

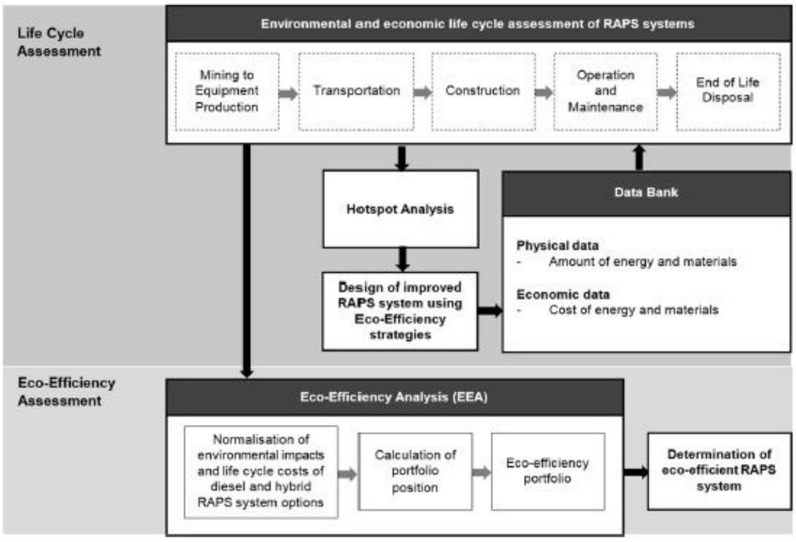

Fig. 1 Eco-efficiency analysis (EEA) framework

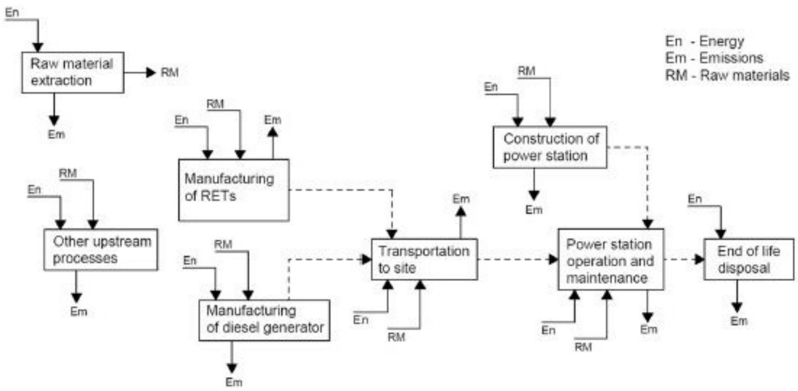

Fig. 2 System boundaries for environmental life cycle assessment

performance of RAPS systems (Bengtsson and Howard 2010a). This includes global warming potential, abiotic resource depletion of fossil fuels and minerals, land use, water depletion, eutrophication potential, acidification potential, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical smog, ozone depletion potential, ionising radiation, human toxicity and respiratory inorganics.

The quantification of materials, energy and emissions data of the life cycle stages of power supply systems is required to develop an LCI (Biswas 2014). Input data were sourced from the power distribution utility to perform inventory analysis. When system specific data were not available, surrogate data were sourced through industry interviews or published literature (Curran 2012). The selected RAPS system has an operating and spinning reserve capacity of 1.28 MW powered by four 320-kW engines. The inventory analysis for this system includes all resource inputs, including materials and energy associated with manufacturing, power generation and disposal of power plants.

1. *Mining to manufacturing of power generation equipment* Surrogate material composition and energy consumption from reliable literature and equipment brochures were used to develop the LCI of the diesel generators. The quantities of material and energy inputs were estimated through mass and energy balance (Schofield 2011).
2. *Construction* The power rating and life time of machineries such as compactor, grader and forklift for constructing the site were sourced from published literature (Chermak 2009). Additional construction materials

such as concrete, steel and aggregate were estimated from equipment construction manuals and manufacturers (MTU Onsite Energy Corporation 2015). The power generation equipment was assumed to be transported from the respective facility to the construction site by ship and lorry. In order to estimate the tonnes-km travelled by sea and land, an online tool (i.e. Google Earth) was used for calculating the distances between origins and destinations.

3. *Operation* This stage includes the material used, energy consumed and emissions released in the operation of the RAPS systems (i.e. renewable energy technologies and the diesel generators). HOMER (Hybrid Optimisation Model for Electric Renewables) was used to estimate the energy consumption during the entire life cycle of the RAPS system (HOMER Energy 2016). The annual time series load data of the distribution utility were incorporated into the software to determine the configuration of distributed generation systems (i.e. equipment power rating and quantity). Diesel was transported from the refinery to the generation site by ship and lorry.
4. *Maintenance* The maintenance stage of the RAPS system involves three activities to retain the prime operating conditions of the diesel generators and RETs. This includes the use of materials such as water for cleaning the solar panels, the distances travelled by maintenance personnel for overhauling and preventive maintenance checks, and for the replacement of inverters in the solar photovoltaic system.
5. *End-of-life disposal* Since there was no information on future planning for the possible use of end-of-life (EoL) power generation equipment, a baseline scenario of landfilling and recycling was modelled using Western Australian waste diversion rates for different types of wastes (Oke et al. 2009). The consideration of remanufacturing strategies for EoL equipment was beyond the scope of this analysis.

All the material and energy input data from the LCIs were incorporated into SimaPro software to estimate the life cycle environmental impacts. The AusLCI unit processes and Ecoinvent 3 emission databases for material, energy and waste that are available in the software were considered in conducting the LCIA analysis. In the absence of local databases in the software, new databases that represent Australia's situation were developed by gathering information on chemicals and energy from the published literature. The inputs and outputs in the inventory are linked to corresponding emission databases to estimate the environmental impacts (Lawania and Biswas 2016). The methodologies used for ascertaining environmental indicators were based on Australian conditions (Bengtsson and Howard 2010a; Renouf et al. 2015). These include the Australian indicator set v2.01, IPCC GWP 100, CML 2 baseline 2001, ReCiPe 2008 and TRACI.

The limitations of current ELCA analysis are as follows:

- The life cycle stages including dismantling of power stations and the transportation of demolition wastes to landfill were excluded.
- Emissions from capital equipment that has a long life span were excluded from the system boundary (Biswas 2009).
- The energy consumption by tools and equipment used for preventive maintenance check and overhauling of the power generating unit was excluded, as this information is not usually recorded.

Life cycle cost estimation

In parallel with ELCA analyses, life cycle costing (LCC) has been conducted for both RAPS systems (Fig. 1). The use of the same functional unit and system boundary for ELCA and LCC would provide a consistent analysis (Kicherer et al. 2007). This LCC was conducted following the guidelines in AS/NZS 4536:1999 Australian/New Zealand Standard life cycle costing application (Standards Australia/Standards New Zealand 2014) to estimate the total life cycle costs.

A bottom-up method involving the definition and estimation of the RAPS system cost components was used to conduct the LCC (Vlachý 2014). Cost data over the entire life cycle of the RAPS system were sourced from relevant Western Australia energy operators and equipment manufacturers in conducting the life cycle cost analysis. The cost components considered in the life cycle cost analysis of the RAPS systems were capital costs, and operation and maintenance costs. The capital costs include the cost of manufacturing, transportation and installation of the power generation equipment, whilst the operation and maintenance costs are associated with the consumption of diesel, use of spare parts and consumables, preventative maintenance and the replacement of parts.

Real costs were used over nominal costs to reduce the uncertainty associated with the inflation of price of technologies and services (Ally and Pryor 2016). This also helps obtain a clear understanding of cost elements and cost drivers of the RAPS system (Standards Australia/Standards New Zealand 2014). The real costs were discounted to consider the time value of money which extends throughout the life cycle of the power plant. A discount rate of 9% (Standards Australia/Standards New Zealand 2014), which is the maximum real discount rate commonly set by the Australian government, has been applied to calculate net present values (NPV).

NPV is commonly used for assessing and comparing the life cycle cost of different grid-connected and remote area energy technologies (Perera et al. 2013). The total life cycle costs were calculated by combining the individual NPV of the capital, and operation and maintenance costs as shown in Eq. 1.

$$LCC = NPV_{capital} + NPV_{O\&M} \quad (1)$$

where LCC is the total life cycle costs of the diesel powered RAPS system (AUD), $NPV_{capital}$ is the NPV for the capital costs (AUD) and $NPV_{O\&M}$ is the NPV for the operation and maintenance costs (AUD).

Application of eco-efficiency strategies

Hotspot analysis has to be conducted to identify the life cycle stage or the input that contributes to the largest share of the environmental impact (Fig. 1) so that relevant mitigation options can be selected (Schofield 2011). Recommendation and application of eco-efficiency strategies were then applied to treat the identified environmental hotspots to reduce the life cycle emissions of the diesel RAPS system. The aims of these strategies are to reduce material and energy intensity, maximise the use of renewable resources, improve material recyclability, enhance service intensity and extend the durability of products (van Berkel 2007).

Incorporation of these strategies could alter the material and energy used during the life cycle stages of the diesel system, and therefore, a follow-up ELCA needs to be done for this improved RAPS system (Lawania and Biswas 2017). In doing this, the data in the inventories have to be revised and then entered into the software to re-estimate impact values. The strategies were compared with the original system to verify their effectiveness in reducing the environmental impacts.

Eco-efficiency assessment

Normalisation of all environmental impacts for 'inhabitant equivalents' for each power supply option presents each of these impacts as the 'number of inhabitants causing the same amount of environmental impact per year' (Kicherer et al. 2007). Weighting is then done with respect to an equivalence factor that represents their relative importance. This presents the environmental impacts into a single value. The steps to aggregate these impacts are as follows:

1. *Normalisation* The calculated life cycle environmental impacts were normalised using the latest Australian gross domestic environmental impacts (Bengtsson and Howard 2010b). Each gross domestic environmental impact GDEI has been expressed in terms of the amount of impact per Australian inhabitant per year (Table 1). The normalised value is calculated using Eq. 2.

$$NV_i = \frac{LCEI_i}{GDEI_i}[Inh] \quad (2)$$

where NV is the normalised impact value of each environmental indicator, GDEI is the gross domestic

Table 1 Normalisation and weighting factors for conducting EEA

Impact category	Unit	Gross domestic environmental impact (GDEI)	Weighting factor (WF) (%)
Global warming	kg CO_2 eq per inhabitant per year	28,690	19.5
Abiotic resource depletion (fossil fuels)	kg Sb eq per inhabitant per year	298.55	4.1
Abiotic resource depletion (minerals)	kg Sb eq per inhabitant per year	1.45	4.1
Land use and ecological diversity	ha. a per inhabitant per year	26	20.9
Water depletion	m^3 H_2O per inhabitant per year	930	6.2
Eutrophication	kg PO_4 eq per inhabitant per year	19	2.9
Acidification	kg SO_2 eq per inhabitant per year	123	3.1
Fresh water aquatic ecotoxicity	kg 1,4-DB eq per inhabitant per year	172	6.9
Marine aquatic ecotoxicity	kg 1,4-DB eq per inhabitant per year	12,117,106	7.7
Terrestrial ecotoxicity	kg 1,4-DB eq per inhabitant per year	88	10.3
Photochemical smog	kg NMVOC per inhabitant per year	75	2.8
Ozone depletion	kg CFC-11 eq per inhabitant per year	0.002	3.9
Ionising radiation	kBq U235 eq per inhabitant per year	1306	1.9
Human toxicity	kg 1,4-DB eq per inhabitant per year	3216	2.7
Respiratory inorganics	kg $PM_{2.5}$ eq per inhabitant per year	45	3.0

CO_2 carbon dioxide, *Sb* antimony, *ha. a* hectare. years, *PO_4* phosphate, *SO_2* sulphur dioxide, *DB* dichlorobenzene, *NMVOC* non-methane volatile organic compounds, *CFC* chlorofluorocarbon, *U235* uranium 235

environmental impact, LCEI is the life cycle environmental impact during the life cycle stages and $i = 1, 2, 3 \cdots 15$ are the impact categories (i.e. global warming potential, abiotic resource depletion (minerals), abiotic resource depletion (fossil fuels), land use and ecological diversity, water depletion, eutrophication potential, acidification potential, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical smog, ozone depletion, ionising radiation, human toxicity and respiratory inorganics).

2. *Weighting* The normalised values of all the environmental indicators were aggregated with the use of an Australian weighting factor (Biswas et al. 2017). These weighting factors represent the magnitude of importance of each environmental impact for Australian conditions (Howard et al. 2009). The normalised environmental impacts are calculated using Eq. 3).

$$\mathrm{EI} = \sum_{i=1}^{15} \mathrm{NV_i} \times \mathrm{WF_i}[\mathrm{Inh}] \tag{3}$$

where EI is the normalised environmental impacts and WF_i is the Australian weighting factor for the impact categories.

Table 1 presents the Australian gross domestic environmental impacts (Bengtsson and Howard 2010b) and weighting values (Howard et al. 2009) used in the EEA.

Similar to the environmental impacts, the total costs of each strategy were normalised using the latest Australian gross domestic product (The World Bank 2015) to present these costs as the number of inhabitants generating the same amount of GDP per year (Eq. 4) (Kicherer et al. 2007).

$$\mathrm{NC} = \frac{\mathrm{LCC}}{\mathrm{GDP}}[\mathrm{Inh}]. \tag{4}$$

Figure 3 shows the normalised costs and normalised environmental impacts of diesel and improved RAPS systems used for eco-efficiency analysis. These are combined into a two-dimensional diagram known as eco-efficiency portfolio (Saling 2013). The horizontal and vertical axes represent the normalised costs and normalised environmental impacts, respectively. The 'lowest number' in both the axes represents the least environmental impact and least cost value, whilst the 'highest number' represents the largest environmental impact and cost impact value. The most eco-efficient RAPS option has the largest perpendicular distance above the diagonal line (Kicherer et al. 2007).

The subsequent steps are followed to calculate the portfolio positions in illustrating the relative eco-efficiency of strategies.

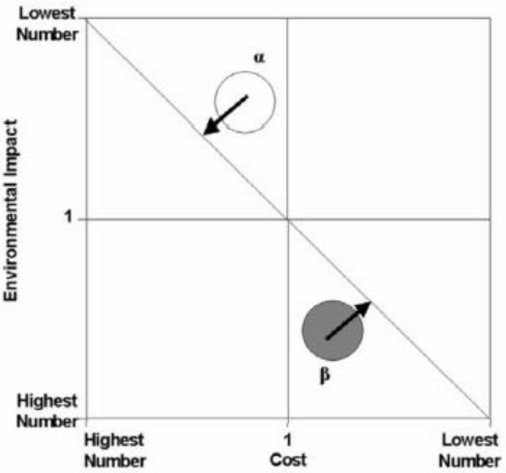

Fig. 3 Sample eco-efficiency portfolio (Kicherer et al. 2007)

1. *Relevance factor* Firstly, the relation of both axes of the eco-efficiency portfolio was quantified to determine the balance between environment and economics. This is calculated by taking the ratio of the average normalised environmental impacts to the average normalised costs (Eq. 5). A value less than 1 suggests that RAPS options with better economic performance are more likely to become more eco-efficient, whereas a value greater than 1 implies that a more environmentally viable RAPS option could be more eco-efficient.

$$\mathrm{R_{e,c}} = \frac{(\sum \mathrm{EI})/\mathrm{j}}{(\sum \mathrm{NC})/\mathrm{j}} \tag{5}$$

where $\mathrm{R_{e,c}}$ is the relevance factor of environment to cost and j is the number of eco-efficiency options considered.

2. *Preliminary portfolio position* The normalised impact/cost of each option is divided by the average normalised impact/cost of all options using Eqs. 6 and 7, respectively (Kicherer et al. 2007).

$$\mathrm{PP}_{e,n} = \frac{\mathrm{EI}_n}{(\mathrm{EI})/j} \tag{6}$$

$$\mathrm{PP}_{c,n} = \frac{\mathrm{NC}_n}{(\mathrm{NC})/j} \tag{7}$$

where $n = 1, 2, 3 \cdots j$ are the eco-efficiency options, $\mathrm{PP}_{e,n}$ is the environment preliminary portfolio position of strategy n and $\mathrm{PP}_{c,n}$ is the cost preliminary portfolio position of strategy n.

3. *Final portfolio position* The preliminary positions are then improved by the relevance factor in order to get a new position in which a balance between environmental impacts and costs exists as shown in Eqs. 8 and 9 (Kicherer et al. 2007).

$$PP'_{e,\alpha} = \left[\left(\sum PP_{e,\alpha}\right)/j + \left[PP_{e,\alpha} - \left(\left(\sum PP_{e,\alpha}\right)/j\right)\right] \cdot \sqrt{(R_{e,c})}\right] / \left[\left(\sum PP_{e,\alpha}/j\right)\right] \quad (8)$$

$$PP'_{c,\alpha} = \left[\left(\sum PP_{c,\alpha}\right)/j + \left[PP_{c,\alpha} - \left(\left(\sum PP_{c,\alpha}\right)/j\right)\right] / \sqrt{(R_{e,c})}\right] / \left[\left(\sum PP_{c,\alpha}/j\right)\right] \quad (9)$$

where $PP'_{e,n}$ is the adjusted environment portfolio position of strategy *n* and $PP'_{c,n}$ is the adjusted cost portfolio position of a strategy *n*.

Results and discussion

Estimation of environmental impacts and life cycle costs of RAPS systems in Western Australia

The development of a life cycle inventory (LCI) is a prerequisite to carry out an LCA analysis. Table 2 presents the LCI of a diesel RAPS system, which consists of mass of materials, energy consumption and tonnes-km transportation value estimated over the life cycle of the diesel RAPS system.

The breakdown of environmental impacts in terms of each life cycle stage of the diesel RAPS system is presented in Table 3. This table also presents the hotspot analysis which identifies the stage causing the most impact for each impact category.

The operation stage has been found to contribute significant portion in all of the impacts, which is 94.93% for global warming potential, 93.02% for mineral depletion, 97.99% for fossil fuel depletion, 99.06% for and land use, 99.61% for water depletion, 92.87% for eutrophication potential, 97.22% for acidification potential, 97.24% for freshwater ecotoxicity, 97.89% for marine ecotoxicity, 98.90% for terrestrial ecotoxicity, 95.61% for photochemical smog, 95.83% for ozone depletion potential, 50.78% for ionising radiation, 98.01% for human toxicity and 95.23% for respiratory inorganics. The power production stage has also been found to be the hotspot in other LCA studies on diesel RAPS systems (Schofield 2011; Smith et al. 2015). Similar LCA studies conducted on standby diesel genset (Benton et al. 2017) and vehicle engine (Li et al. 2013) also found the operation and maintenance as emission intensive stages during the life cycle of a power system.

Eco-efficiency strategy that involves the integration of RETs into the diesel system has been considered as an appropriate environmental mitigation option to reduce the impacts associated in diesel power production. As confirmed

Table 2 Life cycle inventory of a diesel RAPS system

Material/energy	Unit	Quantity
Steel	kg	1080.43
Cast iron	kg	3326.21
Aluminium	kg	228.87
Alloy	kg	188.86
Rubber	kg	27.57
Polymeric compound	kg	27.57
Reinforcing bar	kg	136.77
Diesel	kg	14,793.10
Engine oil	m^3	51.84
Coolant	m^3	25.92
Concrete	m^3	4.07
Aggregate	m^3	2.29
Electricity for moulding, machining and packaging	kWh	13,798.82
Transportation of diesel generators to site	tonnes-km	24,681,423
Transportation of construction material to site	tonnes-km	17,295.89
Transportation of construction equipment to site	tonnes-km	114,851.30
Energy consumption for equipment during construction	MJ	13,540.69
Transportation of personnel for diesel engine overhaul	tonnes-km	63,150

Table 3 Summary of environmental impact breakdown per life cycle stage of the diesel RAPS system in Western Australia (functional unit = 1 MWh of electricity supplied)

Impact Category	Unit	Equipment	Construction	Operation	Maintenance	Disposal
Global warming potential	kg CO_2 eq	0.417	5.50×10^{-1}	429*	5.40×10^{-1}	-1.66×10^{-1}
Abiotic resource depletion (minerals)	kg Sb eq	3.66×10^{-6}	1.30×10^{-6}	8.24×10^{-5}*	1.23×10^{-6}	-1.17×10^{-8}
Abiotic resource depletion (fossil fuels)	kg Sb eq	2.49×10^{-3}	3.85×10^{-3}	6.22*	3.59×10^{-3}	-1.24×10^{-3}
Land use and ecological diversity	ha. a	2.83×10^{-6}	1.52×10^{-6}	7.10×10^{-4}*	2.73×10^{-6}	-3.78×10^{-7}
Water depletion	m^3 H_2O	4.37×10^{-3}	2.76×10^{-3}	2.10*	2.16×10^{-3}	-1.06×10^{-3}
Eutrophication	kg PO_4 eq	1.16×10^{-3}	3.58×10^{-4}	8.26×10^{-1}*	3.09×10^{-4}	-6.46×10^{-5}
Acidification	kg SO_2 eq	1.39×10^{-2}	1.83×10^{-3}	4.23*	1.44×10^{-3}	-4.86×10^{-5}
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	1.39×10^{-3}	1.38×10^{-3}	5.81×10^{-1}*	1.82×10^{-3}	-5.73×10^{-4}
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.40×10^{-2}	1.70×10^{-3}	7.93×10^{-1}*	1.97×10^{-3}	-5.78×10^{-4}
Terrestrial ecotoxicity	kg 1,4-DB eq	7.84×10^{-5}	5.42×10^{-5}	1.52×10^{-2}*	3.85×10^{-5}	-1.66×10^{-6}
Photochemical smog	kg NMVOC	9.85×10^{-4}	2.65×10^{-3}	6.56*	2.37×10^{-3}	-5×10^{-4}
Ozone depletion	kg CFC-11 eq	2.36×10^{-8}	7.25×10^{-8}	1.09×10^{-4}*	5.43×10^{-8}	-4.12×10^{-10}
Ionising radiation	kBq U235 eq	8.47×10^{-2}	2.87×10^{-3}	8.56×10^{-2}*	2.94×10^{-4}	-4.95×10^{-3}
Human toxicity	kg 1,4-DB eq	3.34×10^{-1}	5.65×10^{-2}	19.6*	6.93×10^{-2}	-6.35×10^{-2}
Respiratory inorganics	kg $PM_{2.5}$ eq	4.47×10^{-4}	1.79×10^{-4}	7.71×10^{-1}*	1.44×10^{-4}	-2.32×10^{-5}

The impact values followed by asterisk (*) are identified environmental hotspot for each impact category

by Allan et al. (2015), renewable energy penetration in a decentralised power supply system not only reduces the diesel consumption but also reduces associated environmental emissions.

A 303.75-kW solar PV system with a 500-kVA grid stabilisation and energy storage system were integrated into existing diesel power supply system (i.e. 1.28 MW). The design and technical specification of this renewable energy system which could potentially provide 30% solar PV penetration is based on the information provided by the power distribution utility in the Pilbara region of Western Australia. This hybrid system would require 1350 mono-crystalline solar panels, 135 single-axis solar trackers, 3 units of induction motors for the trackers and 45 inverters. Table 4 presents the supplementary equipment which would require additional inputs for mining to manufacturing, transportation, construction and maintenance stages for estimating additional environmental impacts of the integration of PV into diesel generator. These could, however, potentially reduce the power generation, fuel consumption and maintenance associated with the use of diesel generators.

HOMER simulation software was used to simulate the operation of this hybrid system utilising local solar radiation for Marble Bar. This software determines the power available in the solar panels, compares this power with the current load, determines storage capacity for excess energy and then selects the best source of electricity to meet the projected power deficit. Using the monthly average solar radiation data of 4–8 kWh/m^2 in the region, it was estimated that about 17,475 MWh of solar power could be generated by the hybrid system over the life cycle of 25 years. This could potentially reduce the production of electricity from the diesel generators by 24.67% and associated diesel consumption by 24.47%.

After incorporating this renewable energy into the RAPS system as an eco-efficiency strategy, it was estimated that global warming potential, abiotic resource depletion (fossil fuels), land use, water depletion, eutrophication potential, acidification potential, terrestrial ecotoxicity, photochemical smog, ozone depletion potential and respiratory inorganics would be mitigated by 98.4 kg CO_2 eq, 1.44 kg Sb eq, 0.44×10^{-4} Ha a, 4.48×10^{-1} m^3 H_2O, 1.57×10^{-1} kg PO_4 eq, 9.54×10^{-1} kg SO_2 eq, 8.1×10^{-4} kg 1,4-DB eq, 2.32×10^{-5} kg NMVOC, 1.61×10^{-1} kg CFC-11 eq and 8586 kg $PM_{2.5}$ eq, respectively, in producing one MWh of electricity (Table 5). This mitigation of impacts is mainly due to the reduction in the use of diesel for power generation, transportation and generator maintenance.

An LCC of both diesel and hybrid RAPS systems was also conducted. The present values are briefly grouped into capital cost, and operation and maintenance cost for both the diesel RAPS system and the recommended hybrid system. The life cycle costs were found to be AUD 173.69 for the hybrid system and AUD 166.65 for the diesel system for generating one MWh of electricity. The breakdown of the life cycle costs into cost elements is presented in Table 6.

The operation and maintenance costs of the diesel system were found to contribute significantly (96.8%) to the total life cycle costs followed by the capital costs. Similarly, the hybrid system operation and maintenance costs also contribute the largest share (72%) of the overall life cycle cost followed by the capital costs. Whilst operation and maintenance

Table 4 Life cycle inventory of additional inputs for conversion of diesel to hybrid RAPS system

Material/energy	Unit	Quantity
Glass	tonnes	18.28
Mono-Si wafer	m^2	30.38
Silver paste	kg	42.53
Aluminium paste	kg	179.21
Ammonia	kg	0.72
Phosphoryl chloride	kg	6.26
Ethanol	kg	1005.41
Organic solvents	kg	1.97
Hydrochloric acid (38%)	kg	282.49
Hydrogen fluoride (40%)	kg	258.19
Sodium hydroxide	kg	300.71
Nitrogen	kg	4544.10
Ethylene vinyl acetate	kg	54.68
Aluminium	kg	160.99
Silicon tetrahydride	kg	0.17
Polyvinylfluoride (PVF) film	kg	0.003
Water	tonnes	507.26
Concrete	tonnes	403.77
Steel	tonnes	64.26
Iron	kg	1175.84
Copper	kg	279.50
Aluminium	kg	559
Inverter	pieces	90
Carbon fibre	kg	2000
Converter material	kg	1503
Low-alloy steel	kg	6379.61
Water for solar PV cleaning	m^3	209.94
Electricity for solar PV manufacturing	kWh	55,115.44
Energy consumption for equipment during construction	MJ	145,127.46
Transportation of equipment to site	tonnes-km	1878,001.06
Transportation of replaced inverters	tonnes-km	57,274.21
Transportation of personnel for solar PV maintenance	tonnes-km	670,650

Table 5 Environmental impacts per MWh associated with the integration of renewable energy technologies

Impact category	Unit	Additional emissions from the integration of renewable energy technologies	Savings from renewable energy production
Global warming	kg CO_2 eq	17.6	107
Abiotic resource depletion (fossil fuels)	kg Sb eq	1.04×10^{-1}	1.54
Land use and ecological diversity	ha. a	1.32×10^{-4}	1.76×10^{-4}
Water depletion	m^3 H_2O	3.43×10^{-2}	5.18×10^{-1}
Eutrophication	kg PO_4 eq	4.76×10^{-2}	2.05×10^{-1}
Acidification	kg SO_2 eq	9.61×10^{-2}	1.05
Terrestrial ecotoxicity	kg 1,4-DB eq	2.94×10^{-3}	3.75×10^{-3}
Photochemical smog	kg NMVOC	2.36×10^{-1}	1.63
Ozone depletion	kg CFC-11 eq	3.42×10^{-6}	2.66×10^{-5}
Respiratory inorganics	kg $PM_{2.5}$ eq	2.88×10^{-2}	1.90×10^{-1}

Table 6 Breakdown of life cycle costs for diesel and hybrid RAPS systems in AUD per MWh

Cost elements	Diesel system	Hybrid system
Capital costs ($NPV_{capital}$)	5.38	48.58
Operation and maintenance costs ($NPV_{O\&M}$)	161.27	125.10

cost from the hybrid system is 22.43% lower than that of the diesel system, overall it is less cost competitive due to its high capital costs. The capital cost of this hybrid system is about 803% higher than the cost of the diesel system. Similar results were found by (Lowe and Lloyd 2001).

Eco-efficiency analysis for the selection of RAPS option

The impact indicator values for both RAPS options were normalised, weighted and aggregated in terms of number of inhabitants for comparative analysis using Eqs. 2 and 3. Integration of renewable energy technologies into diesel system would reduce the normalised environmental impact of the hybrid power supply system from 625 to 523 inhabitants equivalent. This is 16.42% lower than the original diesel power supply system. The substantial reduction of most of the environmental impacts resulted in the decrease in the normalised environmental impacts. These results confirm that the maximisation of renewable energy penetration could help achieve a viable eco-efficiency strategy.

The life cycle costs of both systems have also been normalised in terms of number of inhabitants (Eq. 4). The normalised costs of electricity supply from the diesel and hybrid systems are equivalent to the amount of GDP produced by 119 and 124 inhabitants per year, respectively (Table 7). For the same level of electricity service, the hybrid system would be slightly costlier (4.05%) than the diesel system. This result infers that a bit more effort is needed to reduce the cost of renewable energy technologies which is possible either through research and development and suitable market mechanism or by policy changes (e.g. impose a carbon tax on fossil fuel use) (Meng 2014).

The normalised environmental impacts and normalised costs of the diesel and hybrid systems are then used to calculate the eco-efficiency portfolio. These values determine the eco-efficiency performance of the RAPS systems. Using Eq. 5, the calculated relevance factor of environment to cost has been estimated to be 4.7. This infers that environmental impacts are relatively more important than the costs in determining eco-efficiency between options. Using Eqs. 7 to 10, the calculated environment and cost positions for the diesel system ($PP'_{e1} = 1.195$ and $PP'_{c1} = 0.991$) and hybrid system ($PP'_{e2} = 0.805$ and $PP'_{c2} = 1.009$) are plotted in Fig. 4.

The hybrid solar photovoltaic–diesel system provides a more eco-efficient solution than the diesel generating RAPS system (Fig. 4). Whilst the cost of electricity generation from the diesel plant is slightly lower than that of the hybrid system, the former was found to be less eco-efficient than the latter due to higher environmental impacts. This result infers that the integration of renewable energy technologies into the current diesel system would be a more eco-efficient option than diesel generators in the remote areas of Western Australia.

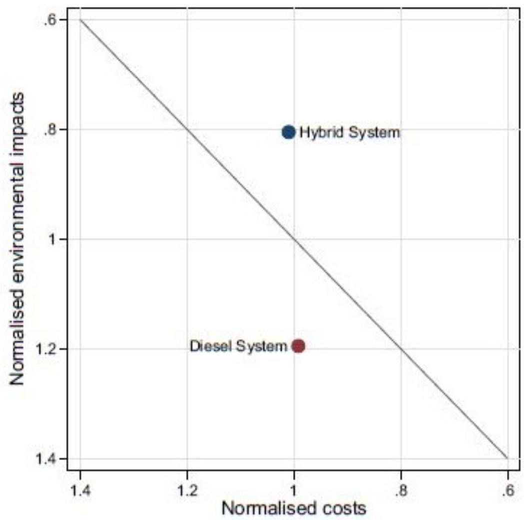

Fig. 4 Portfolio plot for RAPS selection in Marble Bar

Table 7 Eco-efficiency analysis results

	Diesel system	Hybrid system
Normalised environmental impacts (EI)	626	523
Normalised costs (NC)	119	124
Final environmental impact position (PP'_e)	1.195	0.805
Final cost position (PP'_c)	0.991	1.009
Portfolio distance to diagonal line	0.132 below diagonal line	0.132 above diagonal line

Scenario analysis

The installed renewable energy capacity of the base case system was modelled to deliver 24.7% of electricity from renewable energy. A scenario analysis was conducted by increasing the installed capacity of solar photovoltaic (PV) system in the hybrid system halfway through its operational life whilst maintaining power system reliability. Accordingly, the installed capacity of the existing solar PV system has been increased to 450, 600 and 675 kW for conducting the scenario analysis. The life cycle renewable energy production of 450-, 600- and 675-kW solar photovoltaic systems has been estimated to be 22,092 MWh (29.6% of the energy mix), 26,847 MWh (32.4% of the energy mix) and 29,225 MWh (33.3% of the energy mix), respectively. The LCEI and LCC have been conducted for these three hybrid solar photovoltaic–diesel system scenarios for comparative eco-efficiency analysis.

Figure 5 shows that the 450-kW hybrid RAPS scenario offers a more eco-efficient solution than the existing system and other alternative scenarios. The two hybrid scenarios with higher renewable energy capacity were found to be less eco-efficient due to higher cost (0.62–0.99%) and slightly higher environmental impact (0.39–1.94%) compared to the most eco-efficient scenario. Therefore, this eco-efficiency analysis confirms that the higher penetration of renewable energy into the energy mix does not necessarily offer an eco-efficient scenario.

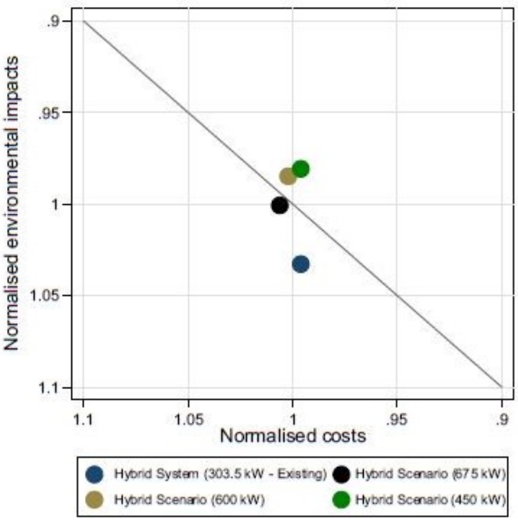

Fig. 5 Scenario analysis for RAPS selection in Marble Bar

Table 8 presents why the continuing increase in solar electricity in the energy mix does not necessarily improve the eco-efficiency performance of RAPS systems. The total life cycle costs of the system increase with the installed capacity of solar PV systems. Operational cost-saving benefits due to reduction in the use of diesel were offset by the incremental capital cost associated with expansion of solar photovoltaic system. Table 8 also presents that installed renewable capacity increases linearly with the environmental impacts in the upstream processes including mining to material production, transportation and construction at a high rate, but not with the decrease in impacts in the downstream processes. As a result, the overall environmental impacts decrease at a certain renewable capacity and then increase at higher installed capacity.

Portfolio analysis can thus be performed to attain an optimum renewable energy and diesel energy mix to provide eco-efficient electricity supply in the remote areas.

Conclusion

This study identifies the strengths and weaknesses of RAPS systems and develops improvement options accordingly for strategic decision-making in remote area power systems. The analysis was designed to develop an eco-efficiency analysis framework to compare the eco-efficiency performance of traditionally used diesel generating systems and hybrid diesel–renewable technologies for remote area power supply. The integration of renewable energy options such as solar photovoltaics into a diesel power system reduces the diesel power operation and reduces some predominant impacts such as GHG emissions during the operational stage by 21% (431–341 kg CO_2 eq) and fossil fuel consumption by 23% (6.23–4.80 kg Sb eq). Whilst the total life cycle cost of the modelled hybrid solar photovoltaic–diesel system is

Table 8 Breakdown of normalised environmental impacts and life cycle costs of the hybrid scenarios

Scenario (kW)	Renewable energy mix (%)	$EI_{upstream}$ (inhabitants equivalent)	$EI_{downstream}$ (inhabitants equivalent)	EI (inhabitants equivalent)	$NPV_{capital}$ (AUD/MWh)	$NPV_{O\&M}$ (AUD/MWh)	LCC (AUD/MWh)
303	24.7	50	472	522	48.58	125.10	173.68
450	29.6	69	441	510	52.52	121.32	173.84
600	32.4	88	423	511	55.11	120.79	175.90
675	33.3	98	417	515	57.70	119.76	177.46

slightly higher than the diesel system, its overall environmental performance makes this a more eco-efficient power supply system.

The eco-efficiency analysis can also be used to attain an optimum solar photovoltaic and diesel mix to provide the most eco-efficient electricity supply system for remote areas. The analysis confirms that increasing the penetration of renewable energy into the energy mix does not necessarily improve the eco-efficiency of the power supply systems.

This EEA framework could be used as a decision-making tool for energy planners to select a cost-competitive environmentally friendly remote area power supply option. Future research will consider the application of this EEA framework in other off-grid locations across Australia under different climatic conditions for a wide range of renewable energy options.

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Appendix B

Table B.1 Estimated quantities of energy and materials for manufacturing of diesel engines

Material/ Energy	Percentage Mass*	Energy Rate*	Unit	Quantity		
				Marble Bar	Coral Bay	Yungngora
Steel	22.14	[-]	kg	1,080.43	1,890.76	867.89
Cast iron	68.16	[-]	kg	3,326.21	5,820.86	2,671.87
Aluminium	4.69	[-]	kg	228.87	400.53	183.85
Alloy	3.87	[-]	kg	188.86	330.50	151.70
Rubber	0.57	[-]	kg	27.57	48.25	22.15
Polymeric compound	0.57	[-]	kg	27.57	48.25	22.15
Electricity	[-]	10.78	kWh	13,798.82	24,147.94	11,772.12

* Percentage mass is presented in kg material/kg diesel engine.
** Energy rate is presented in kWh/kWp.
Assumptions:
1. Mass and energy balance are used to estimate the inputs for diesel engines and are based from Tao Li, Liu, Zhang, and Jiang (2013).
2. Marble Bar has four 320 kW MTU Detroit diesel engines with a mass of 1,220 kg per unit.
3. Coral Bay has seven 320 kW MTU Detroit diesel engine with a mass of 1,220 kg per unit.
4. Yungngora has four 273 kW Scania diesel engines with a mass of 980 kg per unit.

Table B.2 Estimated quantities of energy and materials for manufacturing mono-Si solar PV modules

Material/Energy	Mass/Energy Rate*		Quantity
	Unit	Value	
Glass	kg	60.17	18,276.64
Mono-Si wafer	sq.m.	0.10	30.38
Silver paste	kg	0.14	42.53
Aluminum paste	kg	0.59	179.21
Ammonia	g	2.37	719.89
Phosphoryl chloride	g	20.60	6,257.25
Ethanol	kg	3.31	1,005.41
Organic solvents	g	6.49	1,971.34
Hydrochloric acid (38%)	kg	0.93	282.49
Hydrogen fluoride (40%)	kg	0.85	258.19
Sodium hydroxide	kg	0.99	300.71
Nitrogen	kg	14.96	4,544.10
Ethylene vinyl acetate	kg	0.18	54.68
Aluminum	kg	0.53	160.99
Silicon tetrahydride	g	0.55	167.06

Material/Energy	Mass/Energy Rate*		Quantity
	Unit	Value	
Polyvinylfluoride (PVF) film	g	0.01	3.04
Water	t	1.67	507.26
Electricity	kWh	181.45	55,115.44
* The mass and energy rate are calculated per 1 kWp of mono-Si PV. **Assumptions:** 1. Mass and energy balance are used to estimate the inputs for mono-Si solar PV modules based from Chen et al. (2016). 2. The solar PV modules in Marble Bar has an installed capacity of 303.75 kWp.			

Table B.3 Estimated quantities of materials for manufacturing BOS for single-axis tracking

BOS Component	Material	Unit	Quantity
Tracker	Steel	kg	62,897.73
	Concrete	tonnes	403,772.70
Induction machine	Steel	kg	6.75
	Iron	kg	27.45
	Copper	kg	6.53
	Aluminium	kg	13.05
Inverter		pieces	45
Assumptions: 1. Mass balance is used to estimate the inputs for the tracker and induction machine, and are based from Shingleton (2008) and Andrada et al. (2012). 2. Marble Bar has 135 single axis tracker that is mechanically operated by 3 induction motors. The DC power produced by the solar PV modules are converted into AC power using 45 inverters. 3. The Ecoinvent 3.0 library in SimaPro software has available inverter component, which can be directly used for impact assessment. This has the same specification as the inverter used in the study. The inverter used for analysis has a library name of Inverter, 2.5 kW market for (BP Global) | Alloc Def, U.			

Table B.4 Estimated quantities of materials for manufacturing flywheel energy storage

Flywheel Energy Storage Component	Material	Unit	Quantity
Flywheel	Steel	kg	1,000
Flywheel enclosure	Carbon Fibre	kg	2,000
Converter		kg	1,503
Induction machine	Steel	kg	352.68
	Iron	kg	1,148.39
	Copper	kg	272.98
	Aluminium	kg	545.96
Flywheel system enclosure	Low alloy steel	kg	4,647

Flywheel Energy Storage Component	Material	Unit	Quantity
Assumptions: 1. The material composition and mass balance used to estimate the inputs for the flywheel energy storage are based from Arani et al. 2017, Pena-Alzola, 2011 and Andrada 2012. 2. The Ecoinvent 3.0 library in SimaPro software has available converter component, which can be directly used for impact assessment. This has the same specification as the converter used in the study. The converter used for analysis has a library name of Converter, for electric passenger car (BP Global)| production |Alloc Def, U. 3. The material components used to estimate the inputs for the flywheel energy storage enclosure is from Finelink Holdings Limited (2002).			

Table B.5 Estimated quantities of energy and materials for manufacturing multi-Si solar PV module

Material/Energy	Mass/Energy Rate*		Quantity
	Unit	Value	
Hydrogen	kg	1.80	315
Sodium	kg	8.73	1,527.75
Aluminum powder	kg	10.82	1,893.50
Lime	kg	2.03	355.25
Quartz sand	kg	18.76	3,283.00
Fluorite	kg	48.79	8,538.25
Sulfuric acid	kg	65.06	11,385.50
Oleum	kg	23.36	4,088
NaOH	kg	26.88	4,704
Organic chemicals	kg	14.43	2,525.25
Lime stone	kg	5.87	1,027.25
Sodium nitrate	kg	1.17	204.75
Mirabilite	kg	0.53	92.75
Reused broken glass	kg	48.53	8,492.75
Silver paste	kg	0.092	16.16
TPT film	m^2	9.83	1,720.25
Phosphorus oxychloride	kg	0.021	3.64
Nitrogen	m^3	10.57	1,849.75
Ammonia	kg	0.0025	0.44
Terpineol	kg	0.0061	1.07
Softened water	tonnes	1.14	199.50
Triethyl aluminium	kg	0.55	96.25
Water	m^3	6.69	1,170.75
Polyfoam	kg	24.24	4,242.00
Silicon nitride	kg	0.015	2.66
Lactic acid	kg	0.068	11.95
Metal wire	kg	4.09	715.75
Hydrochloric acid (38%)	kg	0.50	87.50

Material/Energy	Mass/Energy Rate*		Quantity
	Unit	Value	
Hydrofluoric acid (40%)	kg	2.77	484.75
Nitrate (70%)	kg	0.95	166.25
Silicon carbide	kg	14.20	2,485
Silica sand	tonnes	0.06	10.44
Aluminum hydroxide	kg	1.25	218.75
Dolomite	kg	13.12	2,296
Antimony trioxide	kg	0.19	33.25
Aluminum past	kg	0.42	73.50
EVA film	m^2	18.95	3,316.25
Aluminum bar	kg	24.85	4,348.75
Silane	kg	0.00051	0.089
Oxygen	m^2	0.0001	0.017
Ethanol	kg	1.53	267.75
Electricity	kWh	1,456.90	254,957.50
Heavy oil	kg	0.03	4.70
Diesel	kg	1.76	308

* The mass and energy rate are calculated per 1 kWp of multi-SI PV.

Assumptions:

1. Mass and energy balance are used to estimate the inputs for multi-Si solar PV modules and are based from Hong et al. (2016).
2. According to Horizon Power, the solar PV modules in Yungngora has an installed capacity of 175 kW_p.

Table B.6 Estimated quantities of materials for manufacturing BOS for non-tracking modules

BOS Component	Material	Unit	Quantity
Solar PV mount	Aluminium	kg	434.09
	Stainless steel	kg	227.52
	Carbon steel	kg	7,077.18
Lead acid battery	Lead	kg	5,614.68
	Calcium	kg	2.37
	Aluminium	kg	0.79
	Tin	kg	31.63
	Silver	kg	0.79
	Barium sulfate	kg	9.49
	Carbon black	kg	3.16
	Sodium lignosulfate	kg	3.95
	Fibre glass	kg	197.70
	Copper	kg	39.54
	Sulfuric acid	kg	854.06

BOS Component	Material	Unit	Quantity
	Diluted water	kg	593.10
	Polypropylene	kg	593.10
	Integrated circuit	kg	0.016
	Printed wiring board	kg	3.16
	ABS (acrylonitrile-butadiene-styrene)	kg	60.10
Battery system enclosure	Low alloy steel	tonnes	20
Inverter		pieces	16

Assumptions:
1. The material components and mass balance used used to estimate the inputs for the solar PV mount is obtained from Clenergy company.
2. Mass balance is used to estimate the inputs for the lead acid batteries and is based from Kim et al. 2012.
3. The material components used to estimate the inputs for the battery system enclosure is from Finelink Holdings Limited (2002).

Table B.7 Estimated quantities of energy and materials for manufacturing wind generator

Wind Turbine Generator Component	Material/Energy	Unit	Quantity
Tower	Steel	tonnes	45
Nacelle and rotor	Steel	tonnes	27
Foundation	Concrete	tonnes	45
Blades	Epoxy	tonnes	2.25
	Glass fibre	tonnes	0.75
Control panel	Aluminium	tonnes	1.8
Wind turbine generator	Electricity	kWh	67,137

Assumptions:
1. The mass of each wind generator component is obtained from VERGNET (2016).
2. The material composition of each component are based from Schofield (2011), which used a similar wind generator (250 kW WES 30) in the current study.
3. The energy to manufacture the wind turbine generator components is based from Abbes et al. (2014)
4. Coral Bay has three 275 kW wind generator.

Table B.8 Equipment transport information for the hybrid system in Marble Bar

Equipment	Mass (tonnes)	Transport Destination	Distance (km)	Transport Type
Diesel engine (4 units)	4.88	Freidricshafen, Germany to Papenburg, Germany	812	Truck
		Papenburg, Germany to Kwinana Beach, WA	18,034.78	Ship
		Kwinana Beach, WA to Hazelmere, WA	54.7	Truck
		Hazelmere, WA to Marble Bar, WA	1,468	Truck
Mono-Si solar PV (303.75 kWp)	20.25	Laguna, Philippines to Manila, Philippines	57.1	Truck
		Manila, Philippines to Melbourne, Victoria	8,387.71	Ship
		Melbourne, Victoria to Bentleigh, Victoria	14.7	Truck
		Bentleigh, Victoria to Marble Bar, WA	4,475	Truck
Tracker (135 units)	62.90	Laguna, Philippines to Manila, Philippines	57.1	Truck
		Manila, Philippines to Melbourne, Victoria	8,387.71	Ship
		Melbourne, Victoria to Bentleigh, Victoria	14.7	Truck
		Bentleigh, Victoria to Marble Bar, WA	4,475	Truck
Tracker induction machine (3 units)	0.054	Laguna, Philippines to Manila, Philippines	57.1	Truck
		Manila, Philippines to Melbourne, Victoria	8,387.71	Ship
		Melbourne, Victoria to Bentleigh, Victoria	14.7	Truck
		Bentleigh, Victoria to Marble Bar, WA	4,475	Truck
Tracker foundation (135 units)	403.77	Perth, WA to Marble Bar, WA	1,488	Truck
Inverter (45 units)	2.88	Niestetal, Germany to Papenburg, Germany	332	Truck
		Papenburg, Germany to Kwinana Beach, WA	18,034.78	Ship
		Kwinana Beach, WA to Canning Vale, WA	31.1	Truck
		Canning Vale, WA to Marble Bar, WA	1,489sss	Truck
Flywheel energy storage (1 unit)	6.82	Leipzig, Germany to Papenburg, Germany	498	Truck
		Papenburg, Germany to Kwinana Beach, WA	18,034.78	Ship
		Kwinana Beach, WA to Perth, WA	43.1	Truck

Equipment	Mass (tonnes)	Transport Destination	Distance (km)	Transport Type
		Perth, WA to Marble Bar, WA	1,478	Truck
Flywheel container (1 unit)	4.65	Perth, WA to Marble Bar, WA	1,488	Truck

Table B.9 Equipment transport information for the hybrid system in Yungngora

Equipment	Mass (tonnes)	Transport Destination	Distance (km)	Transport Type
Diesel engine (4 units)	3.92	Sodertalje, Sweden to Gothenburg, Sweden	438	Truck
	3.92	Gothenburg, Sweden to Kwinana Beach, WA	18,571.86	Ship
	3.92	Kwinana Beach, WA to Kewdale, WA	44.7	Truck
	3.92	Kewdale, WA to Mount Hardman, WA	2,533	Truck
Multi-Si solar PV (175 kWp)	12.74	Jiangsu Sheng, China to Shanghai, China	141	Truck
	12.74	Shanghai, China to Kwinana Beach, WA	7,493.19	Ship
	12.74	Kwinana Beach, WA to Jandakot, WA	22	Truck
	12.74	Jandakot, WA to Mount Hardman, WA	2,553	Truck
Solar PV mount (100 units)	7.74	Fujian, China to Xiamen, China	45.9	Truck
	7.74	Xiamen, China to Kwinana Beach, WA	6,596.82	Ship
	7.74	Kwinana Beach, WA to Jandakot, WA	22	Truck
	7.74	Jandakot, WA to Mount Hardman, WA	2,553	Truck
Solar PV inverter (6 units)	0.98	Chirnside Park, Victoria to Jandakot, WA	3,469	Truck
	0.98	Jandakot, WA to Mount Hardman, WA	2,553	Truck
Battery inverter (10 units)	0.44	Neckarsulm, Germany to Hamburg, Germany	608	Truck
	0.44	Hamburg, Germany to Kwinana Beach, WA	21,046.13	Ship
	0.44	Kwinana Beach, WA to Jandakot, WA	42.1	Truck
	0.44	Jandakot, WA to Mount Hardman, WA	2,536	Truck
Lead acid battery (120 units)	2.18	Brilon, Germany to Hamburg, Germany	141	Truck

Equipment	Mass (tonnes)	Transport Destination	Distance (km)	Transport Type
	2.18	Hamburg, Germany to Kwinana Beach, WA	7,493.19	Ship
	2.18	Kwinana Beach, WA to Jandakot, WA	22	Truck
	2.18	Jandakot, WA to Mount Hardman, WA	2,553	Truck
Battery system enclosure (1 unit)	20	Perth, WA to Marble Bar, WA	1,123	Truck

Table B.10 Equipment transport information for the hybrid system in Coral Bay

Equipment	Mass (tonnes)	Transport Destination	Distance (km)	Transport Type
Diesel engine (7 units)	8.54	Freidricshafen, Germany to Papenburg, Germany	812	Truck
		Papenburg, Germany to Kwinana Beach, WA	18,034.78	Ship
		Kwinana Beach, WA to Hazelmere, WA	54.7	Truck
		Hazelmere, WA to Marble Bar, WA	1,119	Truck
Wind turbine generator (3 units)	76.8	Ormed, France to Merseille, France	759	Truck
		Merseille, France to Dampier, WA	14,102.98	Ship
		Dampier, WA to Coral Bay, WA	533	Truck
Wind turbine foundation (3 units)	108	Perth, WA to Coral Bay, WA	1,123	Truck
Flywheel energy storage (1 unit)	6.82	Leipzig, Germany to Papenburg, Germany	498	Truck
		Papenburg, Germany to Kwinana Beach, WA	18,034.78	Ship
		Kwinana Beach, WA to Perth, WA	43.1	Truck
		Perth, WA to Coral Bay, WA	1,127	Truck
Flywheel container (1 unit)	4.65	Perth, WA to Coral Bay, WA	1,488	Truck

Table B.11 Specific details on the inputs during the construction of the hybrid system in Marble Bar

Sub-stages		Variable	Quantity
Site preparation		Excavating rate (m^2 per hour)	505.86
		Grading rate (m^2 per hour)	505.86
		Solar farm area (m^2)	22,041
		Generator area (m^2)	6,100
		Total land area (m^2)	28,141
		Excavating (hour)	55.63
		Grading (hour)	55.63
Installation of diesel generator	Material for inertia pad	Foundation length (m)	1.75
		Foundation width (m)	1.30
		Depth of base (m)	0.44
		Density of concrete (kg/m^3)	2,400
		Volume of concrete (m^3)	1.02
		Weight of reinforcing bar (kg)	34.19
		Volume of gravel or sand (m^3)	0.57
		Total volume of concrete (m^3)	4.07
		Total weight of reinforcing bar (kg)	136.77
		Total volume of gravel or sand (m^3)	2.29
	Transportation of concrete	Concrete Density (kg/ m^3)	2,400
		Distance (km)	1,480
		Mass (ton)	2.44
		Input (ton-km)	3,611.20
		Total Input (ton-km)	14,444.80
	Transportation of aggregate	Aggregate Density (kg/ m^3)	2,750
		Distance (km)	421
		Mass (ton)	1.57
		Input (ton-km)	662.71
		Total Input (ton-km)	2,650.86
	Transportation of reinforcing bar	Distance (km)	1,464.00
		Mass (ton)	0.034
		Input (ton-km)	50.06
		Total Input (ton-km)	200.23
Installation of solar PV and trackers	Foundation unloading and placement	Number of hours	6
		Quantity of forklift used	10
		Rate per unit (hours/unit)	0.60
		Total number of hours	81
	Solar PV and tracker unloading and placement	Number of hours	8
		Quantity of forklift used	10
		Rate per unit (hours/unit)	0.80
		Total number of hours	108

Sub-stages		Variable	Quantity
	Transportation of crew	Number of crew	3
		Distance (km)	4,475
		Total Input (passenger-km)	26,850
Transportation of construction equipment	Transportation of forklift	Number of forklift	1
		Distance (km)	1,463
		Mass (ton)	14.65
		Total Input (ton-km)	42,865.90
	Transportation of grader	Number of grader	1
		Distance (km)	1,461
		Mass (ton)	6
		Total Input (ton-km)	17,532
	Transportation of excavator	Number of excavator	1
		Distance (km)	1,480
		Mass (ton)	7.18
		Total Input (ton-km)	21,264.64
	Transportation of concrete mixer	Number of concrete mixer	1
		Distance (km)	1,479.00
		Mass (ton)	2.80
		Total Input (ton-km)	8,282.40
	Transportation of concrete pump	Number of concrete pump	1
		Distance (km)	1,479.00
		Mass (ton)	8.42
		Total Input (ton-km)	24,906.36

Assumptions:

1. Site preparation practice was derived from (Chermak, 2009).
2. The estimation of the materials used to install the diesel engines is based from MTU Onsite Energy Corporation (2015).
3. The transportation of materials for construction are included in the ELCA and these materials were sourced from the closest manufacturer in the RAPS system.
4. The information on solar PV tracker unloading and placement were based from Shingleton (2008).
5. The construction machineries were sourced from the closest contractors, which include TracklinkWA, A1 siteworks, Total Forklift Services and Concrete Equipment Australia Pty. Ltd.

Table B.12 Specific details on the inputs during the construction of the hybrid system in Yungngora

Sub-stages	Variable	Quantity
Site preparation	Excavating rate (m^2 per hour)	505.86
	Grading rate (m^2 per hour)	505.86
	Total land area (m^2)	14,618
	Excavating (hour)	28.90
	Grading (hour)	28.90

Sub-stages		Variable	Quantity
Installation of diesel generator	Material for inertia pad	Foundation length (m)	1.43
		Foundation width (m)	1.01
		Depth of base (m)	0.56
		Density of concrete (kg/m^3)	2,400
		Volume of concrete (m^3)	0.82
		Weight of reinforcing bar (kg)	21.74
		Volume of gravel or sand (m^3)	0.36
		Total volume of concrete (m^3)	3.27
		Total weight of reinforcing bar (kg)	86.97
		Total volume of gravel or sand (m^3)	1.46
	Transportation of concrete	Concrete Density (kg/m^3)	2,400
		Distance (km)	2,539
		Mass (ton)	1.96
		Input (ton-km)	4,976.44
		Total Input (ton-km)	19,905.76
	Transportation of aggregate	Aggregate Density (kg/m^3)	2,750
		Distance (km)	1,137
		Mass (ton)	1
		Input (ton-km)	1,138.16
		Total Input (ton-km)	4,552.66
	Transportation of reinforcing bar	Distance (km)	2,523
		Mass (ton)	0.022
		Input (ton-km)	54.86
		Total Input (ton-km)	219.43
Installation of solar PV modules	Material for foundation	Total number of foundations	100
		Concrete	
		Depth of foundation (m)	1.70
		Diameter of foundation (m)	0.30
		Diameter of pole (m)	0.10
		Volume of concrete (m^3)	0.11
		Total volume of concrete (m^3)	10.63
		Aggregate	
		Thickness of aggregate (m)	0.05
		Diameter of aggregate (m)	0.30
		Volume of aggregate (m^3)	0.0035
		Total volume of aggregate (m^3)	0.35
	Transportation of concrete	Concrete Density (kg/m^3)	2,400
		Distance (km)	2,539
		Mass (ton)	0.26
		Input (ton-km)	647.60

Sub-stages		Variable	Quantity
		Total Input (ton-km)	64,759.73
	Transportation of aggregate	Aggregate Density (kg/m^3)	2,750
		Distance (km)	1,137
		Mass (ton)	0.010
		Input (ton-km)	11.05
		Total Input (ton-km)	1,105.09
Transportation of construction equipment	Transportation of forklift	Number of forklift	1
		Distance (km)	2,522
		Mass (ton)	14.65
		Total Input (ton-km)	73,894.60
	Transportation of grader	Number of grader	1
		Distance (km)	2,521
		Mass (ton)	6
		Total Input (ton-km)	30,252
	Transportation of excavator	Number of excavator	1
		Distance (km)	2,539
		Mass (ton)	7.18
		Total Input (ton-km)	36,480.35
	Transportation of concrete mixer	Number of concrete mixer	1
		Distance (km)	2,539
		Mass (ton)	2.80
		Total Input (ton-km)	14,218.40
	Transportation of concrete pump	Number of concrete pump	1
		Distance (km)	2,539
		Mass (ton)	8.42
		Total Input (ton-km)	42,756.76

Assumptions:

1. Site preparation practice was derived from (Chermak, 2009).
2. The estimation of the materials used to install the diesel engines is based from MTU Onsite Energy Corporation (2015).
3. The transportation of materials for construction are included in the ELCA and these materials were sourced from the closest manufacturer in the RAPS system.
4. The construction machineries were sourced from the closest contractors, which include TracklinkWA, A1 siteworks, Total Forklift Services and Concrete Equipment Australia Pty. Ltd.
4. The amount of material used to install the solar PV panels is based from Clenergy brochure.

Table B.13 Specific details on the inputs during the construction of the hybrid system in Coral Bay

Sub-stages	Variable	Quantity
Site preparation	Excavating rate (m^2 per hour)	505.86
	Grading rate (m^2 per hour)	505.86

Sub-stages		Variable	Quantity
		Area WTG 1 (m^2)	1,611
		Area WTG 2 (m^2)	2,720
		Area WTG 3 (m^2)	1,909
		Area Diesel Generator (m^2)	5,583
		Total land area (m^2)	11,823
		Excavating (hour)	23.37
		Grading (hour)	23.37
Installation of diesel generator	Material for inertia pad	Foundation length (m)	1.75
		Foundation width (m)	1.30
		Depth of base (m)	0.44
		Density of concrete (kg/m^3)	2,400
		Volume of concrete (m^3)	1.02
		Weight of reinforcing bar (kg)	34.19
		Volume of gravel or sand (m^3)	0.57
		Total volume of concrete (m^3)	7.12
		Total weight of reinforcing bar (kg)	239.35
		Total volume of gravel or sand (m^3)	4.01
	Transportation of concrete	Concrete Density (kg/ m^3)	2,400
		Distance (km)	1,132
		Mass (ton)	2.44
		Input (ton-km)	2,762.08
		Total Input (ton-km)	19,334.56
	Transportation of aggregate	Aggregate Density (kg/ m^3)	2,750
		Distance (km)	526
		Mass (ton)	1.57
		Input (ton-km)	828
		Total Input (ton-km)	5,796
	Transportation of reinforcing bar	Distance (km)	1,118
		Mass (ton)	0.034
		Input (ton-km)	38.23
		Total Input (ton-km)	267.59
Construction of wind turbine generator foundation		Dig hole (excavator) (found. per hour)	0.13
		Pour concrete (cement mixer) (found. per hour)	0.19
		Pour concrete (cement pump) (found. per hour)	0.19
		Number of foundations	3
		Excavating (hour)	24
		Cement mixing (hour)	16
		Cement pumping (hour)	16
		Number of forklift	1

Sub-stages		Variable	Quantity
Transportation of construction equipment	Transportation of forklift	Distance (km)	1,134.00
		Mass (ton)	7.18
		Total Input (ton-km)	16,293.31
	Transportation of grader	Number of grader	1
		Distance (km)	1,097
		Mass (ton)	14.65
		Total Input (ton-km)	32,142.10
	Transportation of excavator	Number of excavator	1
		Distance (km)	1,100
		Mass (ton)	6
		Total Input (ton-km)	13,200
	Transportation of concrete mixer	Number of concrete mixer	1
		Distance (km)	1,133
		Mass (ton)	2.80
		Total Input (ton-km)	6,344.80
	Transportation of concrete pump	Number of concrete pump	1
		Distance (km)	1,133
		Mass (ton)	8.42
		Total Input (ton-km)	19,079.72

Assumptions:

1. Site preparation practice and wind generator foundation construction and erection were based from Chermak (2009).
2. The estimation of the materials used to install the diesel engines is based from MTU Onsite Energy Corporation (2015).
3. The transportation of materials for construction are included in the ELCA and these materials were sourced from the closest manufacturer in the RAPS system.
4. The construction machineries were sourced from the closest contractors, which include TracklinkWA, A1 siteworks, Total Forklift Services and Concrete Equipment Australia Pty. Ltd.

Table B.14 HOMER simulation results for the hybrid system in Marble Bar

Year	Production (kWh/yr)						Consumption (kWh/yr)		
	Sunpower	MTU 1	MTU 2	MTU 3	MTU 4	Total	AC Primary Load	Excess Electricity	FES Operation
1	720,424	1,531,057	99,598	-	-	2,351,079	2,125,575	120,385	105,120
2	718,654	1,532,336	99,696	-	-	2,350,686	2,125,575	119,991	105,120
3	716,882	1,533,521	99,697	-	-	2,350,100	2,125,575	119,406	105,120
4	715,108	1,535,093	99,699	-	-	2,349,900	2,125,575	119,205	105,120
5	713,332	1,536,189	99,796	-	-	2,349,317	2,125,575	118,623	105,120
6	711,552	1,537,003	99,894	-	-	2,348,449	2,125,575	117,754	105,120
7	709,768	1,538,013	99,991	-	-	2,347,772	2,125,575	117,077	105,120
8	707,982	1,539,316	99,993	-	-	2,347,291	2,125,575	116,596	105,120
9	706,194	1,540,143	99,995	-	-	2,346,332	2,125,575	115,636	105,120
10	704,404	1,541,260	100,092	-	-	2,345,756	2,125,575	115,061	105,120
11	702,613	1,542,092	100,094	-	-	2,344,799	2,125,575	114,105	105,120
12	700,823	1,543,216	100,287	-	-	2,344,326	2,125,575	113,632	105,120
13	699,032	1,544,342	100,577	-	-	2,343,951	2,125,575	113,256	105,120
14	697,239	1,545,280	100,579	-	-	2,343,098	2,125,575	112,403	105,120
15	695,445	1,546,315	100,580	-	-	2,342,340	2,125,575	111,646	105,120
16	693,650	1,546,971	100,774	-	-	2,341,395	2,125,575	110,701	105,120
17	691,856	1,547,918	100,968	-	-	2,340,742	2,125,575	110,047	105,120
18	690,060	1,548,965	101,065	-	-	2,340,090	2,125,575	109,395	105,120
19	688,263	1,550,014	101,067	-	-	2,339,344	2,125,575	108,649	105,120
20	686,466	1,550,969	101,165	-	-	2,338,600	2,125,575	107,905	105,120
21	684,667	1,552,023	101,167	-	-	2,337,857	2,125,575	107,163	105,120
22	682,868	1,553,082	101,265	-	-	2,337,215	2,125,575	106,520	105,120
23	681,069	1,554,529	101,267	-	-	2,336,865	2,125,575	106,170	105,120
24	679,270	1,555,308	101,461	-	-	2,336,039	2,125,575	105,344	105,120
25	677,469	1,556,474	101,558	-	-	2,335,501	2,125,575	104,807	105,120

Table B.14 continuation

Year	Fuel Consumption (L)					PV Penetration	Renewable Fraction	Electricity In (kWh/yr)	Electricity Out (kWh/yr)
	MTU 1	MTU 2	MTU 3	MTU 4	Total Fuel				
1	423,976	29,599	-	-	453,575	33.89	23.28	2,351,079	2,351,080
2	424,332	29,628	-	-	453,960	33.81	23.22	2,350,686	2,350,686
3	424,655	29,628	-	-	454,283	33.73	23.16	2,350,100	2,350,101
4	425,094	29,629	-	-	454,723	33.64	23.09	2,349,900	2,349,900
5	425,395	29,658	-	-	455,053	33.56	23.03	2,349,317	2,349,318
6	425,612	29,687	-	-	455,299	33.48	22.99	2,348,449	2,348,449
7	425,886	29,716	-	-	455,602	33.39	22.94	2,347,772	2,347,772
8	426,244	29,716	-	-	455,960	33.31	22.88	2,347,291	2,347,291
9	426,460	29,717	-	-	456,177	33.22	22.84	2,346,332	2,346,331
10	426,766	29,746	-	-	456,512	33.14	22.78	2,345,756	2,345,756
11	426,983	29,746	-	-	456,729	33.06	22.74	2,344,799	2,344,800
12	427,295	29,804	-	-	457,099	32.97	22.68	2,344,326	2,344,327
13	427,612	29,890	-	-	457,502	32.89	22.61	2,343,951	2,343,951
14	427,860	29,891	-	-	457,751	32.80	22.57	2,343,098	2,343,098
15	428,137	29,891	-	-	458,028	32.72	22.52	2,342,340	2,342,341
16	428,309	29,949	-	-	458,258	32.63	22.48	2,341,395	2,341,396
17	428,568	30,006	-	-	458,574	32.55	22.43	2,340,742	2,340,742
18	428,852	30,036	-	-	458,888	32.46	22.37	2,340,090	2,340,090
19	429,133	30,036	-	-	459,169	32.38	22.32	2,339,344	2,339,344
20	429,390	30,065	-	-	459,455	32.30	22.27	2,338,600	2,338,600
21	429,672	30,066	-	-	459,738	32.21	22.22	2,337,857	2,337,858
22	429,959	30,095	-	-	460,054	32.13	22.17	2,337,215	2,337,215
23	430,358	30,095	-	-	460,453	32.04	22.10	2,336,865	2,336,865
24	430,565	30,153	-	-	460,718	31.96	22.06	2,336,039	2,336,039
25	430,884	30,182	-	-	461,066	31.87	22.00	2,335,501	2,335,502

Table B.15 HOMER simulation results for the hybrid system in Yungngora

Year	Production (kWh/yr)						Consumption (kWh/yr)	
	Suntech Power	Scania DC12 1	Scania DC12 2	Scania DC12 3	Scania DC12 4	Total	AC Primary Load	Excess Electricity
1	398,457.00	1,299,383.00	80,124.00	-	-	1,777,964.00	1,735,021	29,767
2	395,582.00	1,301,222.00	80,534.00	-	-	1,777,338.00	1,735,021	29,238
3	392,706.00	1,303,555.00	80,780.00	-	-	1,777,041.00	1,735,021	29,059
4	389,831.00	1,304,758.00	81,435.00	-	-	1,776,024.00	1,735,021	28,128
5	386,955.00	1,306,959.00	81,681.00	-	-	1,775,595.00	1,735,021	27,808
6	384,080.00	1,308,611.00	82,090.00	-	-	1,774,781.00	1,735,021	27,083
7	381,204.00	1,310,273.00	82,500.00	-	-	1,773,977.00	1,735,021	26,370
8	378,329.00	1,311,953.00	83,073.00	-	-	1,773,355.00	1,735,021	25,840
9	375,453.00	1,314,056.00	83,319.00	-	-	1,772,828.00	1,735,021	25,411
10	372,578.00	1,315,999.00	83,892.00	-	-	1,772,469.00	1,735,021	25,163
11	369,703.00	1,318,122.00	84,138.00	-	-	1,771,963.00	1,735,021	24,752
12	366,827.00	1,319,847.00	84,465.00	-	-	1,771,139.00	1,735,021	24,017
13	363,952.00	1,321,756.00	84,629.00	-	-	1,770,337.00	1,735,021	23,303
14	361,076.00	1,323,514.00	85,203.00	-	-	1,769,793.00	1,735,021	22,858
15	358,201.00	1,325,448.00	85,612.00	-	-	1,769,261.00	1,735,021	22,429
16	355,325.00	1,327,229.00	86,185.00	-	-	1,768,739.00	1,735,021	22,005
17	352,450.00	1,329,103.00	86,595.00	-	-	1,768,148.00	1,735,021	21,514
18	349,574.00	1,330,987.00	87,250.00	-	-	1,767,811.00	1,735,021	21,284
19	346,699.00	1,332,556.00	87,742.00	-	-	1,766,997.00	1,735,021	20,556
20	343,823.00	1,334,454.00	88,151.00	-	-	1,766,428.00	1,735,021	20,089
21	340,948.00	1,336,690.00	88,397.00	-	-	1,766,035.00	1,735,021	19,798
22	338,072.00	1,338,700.00	88,724.00	-	-	1,765,496.00	1,735,021	19,359
23	335,197.00	1,340,483.00	89,134.00	-	-	1,764,814.00	1,735,021	18,765
24	332,322.00	1,342,513.00	89,625.00	-	-	1,764,460.00	1,735,021	18,514
25	329,446.00	1,343,826.00	90,526.00	-	-	1,763,798.00	1,735,021	17,946

Table B.15 continuation

Year	Fuel Consumption (L)					Battery Loss		
	Scania DC12 1	Scania DC12 2	Scania DC12 3	Scania DC12 4	Total Fuel	Operation Loss	Storage Depletion	Total Loss
1	358,825	24,654	-	-	383,479	2,924	66.60	2,857.40
2	359,298	24,780	-	-	384,078	2,891	66.60	2,824.40
3	359,912	24,855	-	-	384,767	2,847	66.60	2,780.40
4	360,205	25,057	-	-	385,262	2,815	66.60	2,748.40
5	360,776	25,133	-	-	385,909	2,777	66.60	2,710.40
6	361,188	25,259	-	-	386,447	2,747	66.50	2,680.50
7	361,602	25,385	-	-	386,987	2,716	66.50	2,649.50
8	362,031	25,561	-	-	387,592	2,688	66.60	2,621.40
9	362,567	25,637	-	-	388,204	2,659	66.60	2,592.40
10	363,077	25,813	-	-	388,890	2,620	66.60	2,553.40
11	363,618	25,889	-	-	389,507	2,592	66.60	2,525.40
12	364,041	25,990	-	-	390,031	2,563	66.60	2,496.40
13	364,509	26,040	-	-	390,549	2,534	66.60	2,467.40
14	364,957	26,216	-	-	391,173	2,503	66.60	2,436.40
15	365,448	26,342	-	-	391,790	2,467	66.50	2,400.50
16	365,901	26,519	-	-	392,420	2,438	66.50	2,371.50
17	366,372	26,645	-	-	393,017	2,403	66.50	2,336.50
18	366,861	26,846	-	-	393,707	2,370	66.50	2,303.50
19	367,242	26,998	-	-	394,240	2,342	66.50	2,275.50
20	367,718	27,124	-	-	394,842	2,308	66.50	2,241.50
21	368,286	27,199	-	-	395,485	2,276	66.40	2,209.60
22	368,789	27,300	-	-	396,089	2,245	66.40	2,178.60
23	369,226	27,426	-	-	396,652	2,218	66.40	2,151.60
24	369,745	27,577	-	-	397,322	2,188	66.40	2,121.60
25	370,070	27,855	-	-	397,925	2,159	66.40	2,092.60

Table B.15 continuation

Year	Inverter Loss	Rectifier Loss	PV Penetration	Renewable Fraction	Electricity In (kWh/year)	Electricity Out (kWh/year)
1	10,259.00	60.00	22.97	20.49	1,777,964.00	1,777,964.40
2	10,194.00	60.00	22.80	20.36	1,777,338.00	1,777,337.40
3	10,120.00	60.00	22.63	20.21	1,777,041.00	1,777,040.40
4	10,066.00	60.00	22.47	20.11	1,776,024.00	1,776,023.40
5	9,996.00	60.00	22.30	19.96	1,775,595.00	1,775,595.40
6	9,936.00	60.00	22.14	19.85	1,774,781.00	1,774,780.50
7	9,876.00	60.00	21.97	19.73	1,773,977.00	1,773,976.50
8	9,812.00	60.00	21.81	19.60	1,773,355.00	1,773,354.40
9	9,744.00	60.00	21.64	19.46	1,772,828.00	1,772,828.40
10	9,671.00	60.00	21.47	19.32	1,772,469.00	1,772,468.40
11	9,603.00	60.00	21.31	19.18	1,771,963.00	1,771,961.40
12	9,544.00	60.00	21.14	19.06	1,771,139.00	1,771,138.40
13	9,484.00	60.00	20.98	18.94	1,770,337.00	1,770,335.40
14	9,417.00	60.00	20.81	18.81	1,769,793.00	1,769,792.40
15	9,350.00	60.00	20.65	18.67	1,769,261.00	1,769,260.50
16	9,282.00	60.00	20.48	18.54	1,768,739.00	1,768,739.50
17	9,216.00	60.00	20.31	18.40	1,768,148.00	1,768,147.50
18	9,143.00	60.00	20.15	18.26	1,767,811.00	1,767,811.50
19	9,084.00	60.00	19.98	18.14	1,766,997.00	1,766,996.50
20	9,017.00	60.00	19.82	18.01	1,766,428.00	1,766,428.50
21	8,946.00	60.00	19.65	17.86	1,766,035.00	1,766,034.60
22	8,878.00	60.00	19.49	17.73	1,765,496.00	1,765,496.60
23	8,815.00	60.00	19.32	17.60	1,764,814.00	1,764,812.60
24	8,742.00	60.00	19.15	17.46	1,764,460.00	1,764,458.60
25	8,679.00	60.00	18.99	17.33	1,763,798.00	1,763,798.60

Table B.16 HOMER simulation results for the hybrid system in Coral Bay

Variables	Quantity
Production (kWh/yr)	
Vergnet GEV MPC	1,391,499
MTU 1	1827075
MTU 2	236886
MTU 3	1927
MTU 4	-
MTU 5	-
MTU 6	-
MTU 7	-
Total	3,457,387
Consumption (kWh/yr)	
AC primary load	3,261,231
Excess electricity	91,036
FES operation	105,120
Fuel Consumption (L)	
MTU 1	500,807
MTU 2	68,993
MTU 3	574
MTU 4	-
MTU 5	-
MTU 6	-
MTU 7	-
Total fuel	570,374
Other Variables	
Wind penetration	42.67
Renewable fraction	36.65
Electricity in (kWh/yr)	3,457,387
Electricity out (kWh/yr)	3,457,387

Table B.17 Fuel transport information

RAPS	Mass (tonnes)	Transport Destination	Distance (km)	Transport Type	Quantity (tonnes-km)
Marble Bar	9,473.59	Kwinana Beach, WA to Wedgefield, WA	1,816.81	Ship	17,211,708.76
	9,473.59	Wedgefield, WA to Marble Bar, WA	197	Truck	1,866,296.77
Coral Bay	9451.1	Kwinana Beach, WA to Geraldton, WA	455	Truck	4,300,250.50
	9451.1	Geraldton, WA to Coral Bay, WA	708	Truck	6,691,378.80
Yungngora	8091.43	Kwinana Beach, WA to Broome, WA	2550.2	Ship	20,634,764.79
	8091.43	Broome, WA to Yungngora, WA	384	Truck	3,107,109.12

Assumptions:
1. The amount of diesel consumed by each hybrid system was estimated using HOMER software.
2. The mode of diesel transportation is based on correspondence with BP Australia, Recharge Petroleum and Refuels Australia.
3. The transportation distances were estimated using Google Earth software and an online port distance calculator (www.sea-distances.org).

Table B.18 Estimated quantities of engine oil and coolant

RAPS	Hours of Operation	Number of Oil Replacement	Engine Oil Consumption (L)	Number of Coolant Replacement	Coolant Consumption (L)
Marble Bar	224,385	897.54	40,389.3	448.77	20,194.65
Coral Bay	204,800	819.2	36,864	409.6	18432
Yungngora	241,947	604.87	19,960.63	483.89	10,645.67

Assumption:
1. Based on MTU GmBh 2003, the maintenance level for changing the engine oil for a MTU Detroit diesel engine is every 250 hours of operation and every 500 hours for replacing the coolant. The quantity required in replacing the materials is 45 L for the engine oil and 45 L for the coolant.
2. Based on Scania Engine and Industrial engine, the maintenance level for changing the engine oil for a Scania diesel engine is every 400 hours of operation and every 500 hours for replacing the coolant. The quantity required in replacing the materials is 33 L for the engine oil and 22 L for the coolant.

Table B.19 Estimated quantities of materials and energy during the maintenance stage of the hybrid system in Marble Bar

Material/Energy	Unit	Quantity
Water (solar PV cleaning)	m^3	209.94
Inverter	pieces	45
Transportation of inverter	tonnes-km	57,274.21
Transportation of personnel for diesel engine overhaul	person-km	63,150.00
Transportation of personnel for solar PV maintenance	person-km	670,650.00
Assumptions: 1. The solar panel cleaning was included to avoid solar power reduction due to dust formation (ABCSE; Hou et al., 2016; Kannan et al., 2006; NREL, 2015). The amount of water required to clean the solar PV panels was 3.5 to 5 litres per m^2 annually (Eco Cleaning System). 2. The inverters were assumed to be replaced once using the same equipment (e.g. SMA SunnyBoy 7000HV) (NREL, 2015). 3. The maintenance of the solar PV system and diesel engines only includes the transportation of personnel to the power generating site. Since the information on actual contractor is proprietary, the closest available maintenance service providers were assumed for the study.		

Table B.20 Estimated quantities of materials and energy during the maintenance stage of the hybrid system in Yungngora

Material/Energy		Unit	Quantity
Water (solar PV cleaning)		m^3	142.35
Inverter		pieces	16.00
Lead-acid battery	Lead	kg	5,614.68
	Calcium	kg	2.37
	Aluminium	kg	0.79
	Tin	kg	31.63
	Silver	kg	0.79
	Barium sulfate	kg	9.49
	Carbon black	kg	3.16
	Sodium lignosulfate	kg	3.95
	Fibreglass	kg	197.70
	Copper	kg	39.54
	Sulfuric acid	kg	854.06
	Diluted water	kg	593.10
	Polypropylene	kg	593.10
	Integrated circuit	kg	0.02
	Printed wiring board	kg	3.16
	ABS (acrylonitrile-butadiene-styrene)	kg	60.10

Material/Energy	Unit	Quantity
Transportation of inverter	tonnes-km	16,551.70
Transportation of lead-acid battery	tonnes-km	166,986.28
Transportation of personnel for diesel engine overhaul	person-km	170,700
Transportation of personnel for solar PV maintenance	person-km	382,950

Assumptions:
1. The solar panel cleaning was included to avoid solar power reduction due to dust formation (ABCSE; Hou et al., 2016; Kannan et al., 2006; NREL, 2015). The amount of water required to clean the solar PV panels was 3.5 to 5 litres per m^2 annually (Eco Cleaning System).
2. The inverters and batteries were assumed to be replaced once using the same equipment (e.g. Selectronic SPLC-1202, Kaco Powador 20.0 TL3 and Hoppecke 8OPzV1000) (NREL, 2015).
3. The maintenance of the solar PV system and diesel engines only includes the transportation of personnel to the power generating site. Since the information on actual contractor is proprietary, the closest available maintenance service providers were assumed for the study.

Table B.21 Estimated quantities of materials and energy during the maintenance stage of the hybrid system in Coral Bay

Material/Energy	Unit	Quantity
Steel (gearbox replacement)	kg	5,610.00
Transportation of gearbox	tonnes-km	86,365.84
Transportation of personnel for diesel engine overhaul	person-km	63,120
Transportation of personnel for wind turbine generator maintenance	person-km	134,760

Assumptions:
1. The gearbox of the wind generators was replaced once (Demir & Taşkın, 2013; Guezuraga et al., 2012; Morton, 2012). The material composition and mass of the gearbox are based from Energiforsk (2016).
2. The maintenance of the wind generators and diesel engines only includes the transportation of personnel to the power generating site. Since the information on actual contractor is proprietary, the closest available maintenance service providers were assumed for the study.

Appendix C

Table C.1 Breakdown of environmental impacts in terms of life cycle stages for the hybrid system in Marble Bar (FU = 1 MWh of electricity generation)

Environmental Impacts	Unit	Mining to Material Production	Construction	Operation	Maintenance	End-of-Life Disposal	Total
Global warming potential	kg CO_2 eq	8.85	4.41	332.35	3.35	0.008	348.97
Mineral depletion	kg Sb eq	4.98E-4	1E-5	6E-5	4E-5	4E-10	0.0006
Fossil fuel depletion	kg Sb eq	0.05	0.03	4.83	0.02	4E-5	4.93
Land use and ecological diversity	Ha a	7E-5	1E-5	0.0006	2E-5	1E-8	0.0006
Water depletion	m^3 H_2O	0.007	0.02	1.63	0.02	1E-5	1.67
Eutrophication	kg PO_4 eq	0.02	0.003	0.64	0.004	0.0002	0.67
Acidification	kg SO_2 eq	0.05	0.02	3.28	0.01	0.0008	3.36
Freshwater ecotoxicity	kg 1,4-DB eq	0.60*	0.01	0.45	0.03	3E-5	1.09
Marine ecotoxicity	kg 1,4-DB eq	0.62*	0.01	0.62	0.03	3E-5	1.28
Terrestrial ecotoxicity	kg 1,4-DB eq	0.002	0.0004	0.01	0.0003	2E-8	0.01
Photochemical smog	kg NMVOC	0.03	0.02	5.08	0.02	0.002	5.15
Ozone depletion	kg CFC-11 eq	2.35E-6	6E-7	8E-*	4E-7	8E-11	9E-5
Ionising radiation	kBq U235 eq	0.6	0.02	0.07	0.02	2E-5	0.68
Human toxicity	kg 1,4-DB eq	10.2	0.52	15.17	1.44	0.003	27.31
Respiratory inorganics	kg $PM_{2.5}$ eq	0.02	0.001	0.60	0.001	1E-5	0.62

Values highlighted are hotspot(s) of the corresponding environmental impact.

Table C.2 Normalised impact assessment values (equivalent inhabitants $\times 10^{-3}$) for the hybrid system in Marble Bar (FU = 1 MWh of electricity generation)

Environmental Impacts	Mining to Material Production	Construction	Operation	Maintenance	End-of-Life Disposal	Total
Global warming potential	0.31	0.15	11.58	0.12	0.0003	12.16
Mineral depletion	0.34	0.007	0.04	0.02	3E-7	0.42
Fossil fuel depletion	0.16	0.11	16.17	0.07	0.0001	16.50
Land use and ecological diversity	0.003	0.0004	0.02	0.0007	4E-7	0.03
Water depletion	0.007	0.02	1.75	0.02	1E-5	1.80
Eutrophication	1.27	0.16	33.66	0.19	0.01	35.30
Acidification	0.44	0.13	26.63	0.09	0.006	27.29
Freshwater ecotoxicity	3.50	0.07	2.62	0.17	0.0002	6.36
Marine ecotoxicity	5E-5	1E-6	5E-5	3E-6	2E-9	0.0001
Terrestrial ecotoxicity	0.03	0.005	0.13	0.004	3E-7	0.17
Photochemical smog	0.44	0.30	67.71	0.20	0.02	68.67
Ozone depletion	1.17	0.29	42.10	0.18	4E-5	43.74
Ionising radiation	0.44	0.02	0.05	0.02	2E-5	0.52
Human toxicity	3.17	0.16	4.72	0.45	0.0008	8.49
Respiratory inorganics	0.49	0.03	13.26	0.03	0.0003	13.81

Table C.3 Breakdown of environmental impacts in terms of life cycle stage for the hybrid system in Yungngora (FU = 1 MWh of electricity generation)

Environmental Impacts	Unit	Mining to Material Production	Construction	Operation	Maintenance	End-of-Life Disposal	Total
Global warming potential	kg CO_2 eq	2.25	1.97	360.08	3.60	0.01	367.92
Mineral depletion	kg Sb eq	0.0004	5E-6	8E-5	0.0004*	-7E-12	0.0009
Fossil fuel depletion	kg Sb eq	0.01	0.01	5.11	0.02	2E-5	5.16
Land use and ecological diversity	Ha a	1E-5	5E-6	0.0007	2E-5	3E-9	0.0007
Water depletion	m^3 H_2O	0.02	0.009	1.75	0.02	2E-6	1.79
Eutrophication	kg PO_4 eq	0.005	0.002	0.68	0.005	0.0007	0.69
Acidification	kg SO_2 eq	0.01	0.008	3.49	0.01	0.003	3.52
Freshwater ecotoxicity	kg 1,4-DB eq	0.09	0.005	0.49	0.05	1E-5	0.64
Marine ecotoxicity	kg 1,4-DB eq	0.08	0.006	0.67	0.05	1E-5	0.81
Terrestrial ecotoxicity	kg 1,4-DB eq	0.0004	0.0002	0.01	0.0003	7E-9	0.01
Photochemical smog	kg NMVOC	0.008	0.01	5.42	0.02	0.006	5.46
Ozone depletion	kg CFC-11 eq	1E-7	3E-7	9E-5	4E-7	6E-12	9E-5
Ionising radiation	kBq U235 eq	0.23	0.01	0.08	0.07	10E-6	0.39
Human toxicity	kg 1,4-DB eq	2.75	0.19	16.81	1.89	0.001	21.65
Respiratory inorganics	kg $PM_{2.5}$ eq	2.83E-03	0.0007	0.63	0.002	4E-5	0.63

Values highlighted are hotspot(s) of the corresponding environmental impact.

Table C.4 Normalised impact assessment values (inhabitants equivalent $\times 10^{-3}$) for the hybrid system in Yungngora (FU = 1 MWh of electricity generation)

Environmental Impacts	Mining to Material Production	Construction	Operation	Maintenance	End-of-Life Disposal	Total
Global warming	0.08	0.07	12.55	0.13	0.0004	12.82
Mineral depletion	0.27	0.003	0.06	0.25	-5E-9	0.59
Fossil fuel depletion	0.05	0.05	17.12	0.08	5E-5	17.29
Land use and ecological diversity	0.0005	0.0002	0.03	0.0008	1E-7	0.03
Water depletion	0.02	0.01	1.88	0.02	2E-6	1.93
Eutrophication	0.28	0.08	35.94	0.24	0.04	36.58
Acidification	0.09	0.06	28.33	0.11	0.02	28.62
Freshwater ecotoxicity	0.50	0.03	2.87	0.31	7E-5	3.71
Marine ecotoxicity	7E-6	5E-7	6E-3	4E-6	9E-10	7E-5
Terrestrial ecotoxicity	0.004	0.002	0.15	0.0004	8E-8	0.16
Photochemical smog	0.10	0.15	72.23	0.21	0.08	72.78
Ozone depletion	0.05	0.13	44.61	0.18	3E-6	44.97
Ionising radiation	0.17	0.009	0.06	0.06	7E-6	0.30
Human toxicity	0.86	0.06	5.23	0.59	0.0004	6.73
Respiratory inorganics	0.06	0.02	13.98	0.03	9E-4	14.09

Table C.5 Breakdown of environmental impacts in terms of life cycle stage for the hybrid system in Coral Bay (FU = 1 MWh of electricity generation)

Environmental Impacts	Unit	Mining to Material Production	Construction	Operation	Maintenance	End-of-Life Disposal	Total
Global warming potential	kg CO_2 eq	8.19	1.29	284.45	1.11	0.009	295.04
Mineral depletion	kg Sb eq	0.0004	3E-6	0.0001	1E-5	4E-10	0.0005
Fossil fuel depletion	kg Sb eq	0.05	0.009	4.02	0.007	4E-5	4.09
Land use and ecological diversity	Ha a	4E-5	4E-6	0.0003	5E-6	10E-9	0.0003
Water depletion	m^3 H_2O	0.11	0.005	1.40	0.008	9E-6	1.52
Eutrophication	kg PO_4 eq	0.02	0.001	0.52	0.001	0.0003	0.54
Acidification	kg SO_2 eq	0.04	0.008	2.66	0.004	0.001	2.72
Freshwater ecotoxicity	kg 1,4-DB eq	0.52	0.004	0.40	0.03	3E-5	0.96
Marine ecotoxicity	kg 1,4-DB eq	0.54	0.005	0.55	0.03	3E-5	1.12
Terrestrial ecotoxicity	kg 1,4-DB eq	0.002	0.0002	0.01	0.0001	2E-8	0.01
Photochemical smog	kg NMVOC	0.03	0.009	4.12	0.005	0.002	4.16
Ozone depletion	kg CFC-11 eq	2E-6	2E-7	7E-5	9E-8	6E-11	7E-5
Ionising radiation	kBq U235 eq	1.9	0.03	0.05	0.08	2E-5	2.07
Human toxicity	kg 1,4-DB eq	8.45	0.16	13.79	0.35	0.003	22.75
Respiratory inorganics	kg $PM_{2.5}$ eq	0.02	0.0007	0.49	0.001	2E-5	0.51

Values highlighted are hotspot(s) of the corresponding environmental impact.

Table C.6 Normalised impact assessment values (equivalent inhabitants ×10-3) for the hybrid system in Coral Bay (FU = 1 MWh of electricity generation)

Environmental Impacts	Mining to Material Production	Construction	Operation	Maintenance	End-of-Life Disposal	Total
Global warming potential	0.29	0.05	9.91	0.04	0.0003	10.28
Mineral depletion	0.27	0.002	0.08	0.01	3E-7	0.36
Fossil fuel depletion	0.17	0.03	13.47	0.02	0.0001	13.69
Land use and ecological diversity	0.002	0.0002	0.01	0.0002	4E-7	0.01
Water depletion	0.11	0.005	1.50	0.009	1E-5	1.63
Eutrophication	1.14	0.06	27.32	0.06	0.01	28.60
Acidification	0.36	0.06	21.62	0.03	0.009	22.08
Freshwater ecotoxicity	3.04	0.02	2.34	0.19	0.0002	5.61
Marine ecotoxicity	4E-5	5E-7	5E-5	3E-6	2E-9	9E-5
Terrestrial ecotoxicity	0.02	0.002	0.13	0.001	3E-7	0.16
Photochemical smog	0.37	0.11	54.94	0.06	0.03	55.52
Ozone depletion	1.02	0.09	35.33	0.05	3E-5	36.49
Ionising radiation	1.46	2.60×10^{-2}	0.04	0.06	2E-5	1.58
Human toxicity	2.63	5.02×10^{-2}	4.29	0.11	0.0008	7.07
Respiratory inorganics	0.38	1.67×10^{-2}	10.87	0.03	0.0004	11.29

Table C.7 Comparative analysis of environmental impacts of the hybrid systems in Marble Bar, Coral Bay and Yungngora (FU = 1 MWh of electricity generation)

Environmental Impacts	Characterisated Values				Normalisated Values (inhabitants x10^{-3})		
	Unit	Marble Bar	Coral Bay	Yungngora	Marble Bar	Coral Bay	Yungngora
Global warming potential	kg CO_2 eq	349	295	368	12	10	13
Abiotic resource depletion (minerals)	kg Sb eq	0.0006	0.0005	0.0008	0.4	0.3	0.6
Abiotic resource depletion (fossil fuels)	kg Sb eq	5	4	5	17	14	17
Land use and ecological diversity	Ha a	0.0006	0.0004	7E-4	0.03	0.01	0.03
Water depletion	m^3 H_2O	1.7	1.5	1.8	1.8	1.6	2
Eutrophication	kg PO_4 eq	0.7	0.5	0.7	35	29	37
Acidification	kg SO_2 eq	3.4	2.7	3.5	27	22	29
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	1	1	0.6	6.4	5.6	3.7
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.3	1	0.8	0.0001	9E-5	7E-5
Terrestrial ecotoxicity	kg 1,4-DB eq	0.02	0.01	0.01	0.17	0.16	0.16
Photochemical smog	kg NMVOC	5	4	5.5	68.7	55.5	72.8
Ozone depletion	kg CFC-11 eq	9E-5	7E-5	9E-5	44	36.5	45
Ionising radiation	kBq U235 eq	0.7	2	0.4	0.5	1.6	0.30
Human toxicity	kg 1,4-DB eq	27	23	22	8.5	7	6.7
Respiratory inorganics	kg $PM_{2.5}$ eq	0.6	0.5	0.6	13.8	11.3	14

Characterised values highlighted in green have the least environmental impact amongst the hybrid systems

Table C.8 Environmental impacts associated with additional installed renewable energy capacity and environmental impact saving potential for the solar PV-diesel hybrid system in Marble Bar (FU=1 MWh electricity supplied)

Environmental Impacts	**Unit**	**Environmental Impacts Associated with Additional Renewable Energy Capacity**				**Environmental Impact Saving Potential**			
		337.5 kW_p (MB3)	**450 kW_p (MB4)**	**562.5 kW_p (MB5)**	**675 kW_p (MB6)**	**337.5 kW_p (MB3)**	**450 kW_p (MB4)**	**562.5 kW_p (MB5)**	**675 kW_p (MB6)**
Photochemical smog	kg NMVOC	0.007	0.02	0.04	0.05	0.07	0.3	0.4	0.5
Ozone depletion	kg CFC-11 eq	1.6E-7	5E-7	8E-7	1E-6	1E-6	5E-6	7E-6	9E-6
Eutrophication	kg PO_4 eq	0.002	0.007	0.01	0.02	0.009	0.04	0.05	0.07
Acidification	kg SO_2 eq	0.007	0.03	0.04	0.06	0.05	0.2	0.3	0.33
Fossil fuel depletion	kg Sb eq	0.01	0.03	0.05	0.07	0.08	0.3	0.4	0.5
Respiratory inorganics	kg $PM_{2.5}$ eq	0.002	0.01	0.02	0.03	0.09	0.03	0.05	0.06
Global warming potential	kg CO_2 eq	1.6	5.3	9	12.7	5	19	28.3	34

Table C.9 Environmental impacts associated with the integration of rooftop solar PV on residential houses and environmental impacts savings potential for the solar PV-diesel hybrid system in Yungngora (FU=1 MWh electricity generated)

Environmental Impacts	Unit	Environmental Impacts Associated with the Integration of Rooftop Solar PV		Environmental Impacts Savings Potential	
		105 kW_p Installation Scenario (Yg3)	207 kW_p Installation Scenario (Yg4)	105 kW_p Installation Scenario (Yg3)	207 kW_p Installation Scenario (Yg4)
Global warming potential	kg CO_2 eq	0.24	0.5	17	27
Fossil fuel depletion	kg Sb eq	0.002	0.003	0.33	0.46
Eutrophication	kg PO_4 eq	0.0009	0.002	0.18	0.20
Acidification	kg SO_2 eq	0.002	0.003	0.76	0.82
Photochemical smog	kg NMVOC	0.001	0.002	1.41	1.51
Ozone depletion	kg CFC-11 eq	4E-8	7E-8	6E-6	8E-6
Respiratory inorganics	kg $PM_{2.5}$ eq	0.0003	0.0005	0.04	0.05

Table C.10 Environmental impacts associated with additional installed renewable energy capacity and environmental impact savings potential (FU=1 MWh electricity generated)

Environmental Impacts	Unit	Environmental Impacts Associated with Additional Renewable Energy Capacity					Environmental Impact Savings Potential				
		200 kW (Yg5)	300 kW (Yg6)	400 kW (Yg7)	500 kW (Yg8)	600 kW (Yg9)	200 kW (Yg5)	300 kW (Yg6)	400 kW (Yg7)	500 kW (Yg8)	600 kW (Yg9)
Global warming potential	kg CO2 eq	1.14	1.66	2.30	2.94	3.58	10.36	37.89	56.74	71.24	81.62
Fossil fuel depletion	kg Sb eq	7.91×10^{-3}	1.13×10^{-2}	1.53×10^{-2}	1.94×10^{-2}	2.35×10^{-2}	0.14	0.52	0.79	1.00	1.15
Eutrophication	kg PO4 eq	1.99×10^{-3}	2.19×10^{-3}	3.47×10^{-3}	4.80×10^{-3}	6.12×10^{-3}	1.98×10^{-2}	7.24×10^{-2}	0.11	0.14	0.15
Acidification	kg SO2 eq	4.82×10^{-3}	6.58×10^{-3}	9.91×10^{-3}	1.33×10^{-2}	1.67×10^{-2}	0.10	0.37	0.55	0.69	0.79
Photochemical smog	kg NMVOC	5.52×10^{-3}	8.44×10^{-3}	1.21×10^{-2}	1.57×10^{-2}	1.94×10^{-2}	0.16	0.58	0.86	1.08	1.23
Ozone depletion	kg CFC-11 eq	1.58×10^{-7}	1.94×10^{-7}	2.54×10^{-7}	3.15×10^{-7}	3.76×10^{-7}	2.49×10^{-6}	9.16×10^{-6}	1.38×10^{-5}	1.75×10^{-5}	2.01×10^{-5}
Respiratory inorganics	kg PM2.5 eq	6.49×10^{-4}	9.07×10^{-4}	1.43×10^{-3}	1.97×10^{-3}	2.50×10^{-3}	1.84×10^{-2}	6.69×10^{-2}	9.98×10^{-2}	0.12	0.14

Table C.11 Environmental impacts associated with the integration of rooftop solar PV on residential houses and environmental impacts savings potential for the wind-diesel hybrid system in Coral Bay (FU=1 MWh electricity generated)

Environmental Impacts	Unit	Environmental Impacts Associated with the Integration of Rooftop Solar PV		Environmental Impacts Savings Potential	
		kW_p Installation Scenario (Yg3)	kW_p Installation Scenario (Yg4)	kW_p Installation Scenario (Yg3)	kW_p Installation Scenario (Yg4)
Global warming potential	kg CO_2 eq	0.24	0.5	17	27
Fossil fuel depletion	kg Sb eq	0.002	0.003	0.33	0.46
Eutrophication	kg PO_4 eq	0.0009	0.002	0.18	0.20
Acidification	kg SO_2 eq	0.002	0.003	0.76	0.82
Photochemical smog	kg NMVOC	0.001	0.002	1.41	1.51
Ozone depletion	kg CFC-11 eq	4E-8	7E-8	6E-6	8E-6
Respiratory inorganics	kg $PM_{2.5}$ eq	0.0003	0.0005	0.04	0.05

Appendix D

Table D.1 Cost breakdown structure and cost information source of the hybrid systems in Western Australia

Life Cycle Cost Elements	Data Source		
	Marble Bar	**Coral Bay**	**Yungngora**
Equipment acquisition			
Acquisition of diesel engines	Penske Power Systems	Penske Power Systems	Penske Power Systems
Acquisition of solar PV system and BOS	MPower, SMA		MPower
Acquisitive of wind turbine generators		(BREE, 2013; CO2CRC et al., 2015)	
Acquisition of flywheel energy storage	(Rossow, 2003)	(Rossow, 2003)	
Installation of diesel engines	Penske Power Systems	Penske Power Systems	Penske Power Systems
Transportation of diesel engines	Freight Exchange	Freight Exchange	Freight Exchange
Installation of solar photovoltaic and balance of system	MPower		MPower
Transportation of solar photovoltaic and balance of system	Freight Exchange		Freight Exchange
Installation of flywheel energy storage	(Rossow, 2003)	(Rossow, 2003)	
Operation and maintenance			
Diesel power production	HOMER software, Recharge Petroleum	HOMER software, Refuels Australia	HOMER software, Recharge Petroleum
Routine maintenance of diesel engines	Diesel Engine Services & Spares Power	Diesel Engine Services & Spares Power	Diesel Engine Services & Spares Power
Routine operation and maintenance of solar photovoltaic and balance of system	(BREE, 2013; CO2CRC et al., 2015)		(BREE, 2013; CO2CRC et al., 2015)
Spare parts usage of solar PV system and BOS	SMA		MPower, Selectronics, Hoppecke
Routine operation and maintenance of wind turbine generators		(BREE, 2013; CO2CRC et al., 2015)	
Routine maintenance of flywheel energy storage	(Rossow, 2003)	(Rossow, 2003)	
Spare parts usage of flywheel energy storage	(Rossow, 2003)	(Rossow, 2003)	

Table D.2 Breakdown of the capital cost for the hybrid system in Marble Bar

Cost Element	Reference Year	Base Year	NPV in Reference Year (AUD)	NPV in Base Year (AUD)
Acquisition of diesel engines[1,10]	2017	2007	268,000	211,415
Acquisition of solar PV system and BOS[2,3,4,11]	2017	2007	678,693	1,696,734
Acquisition of flywheel energy storage[5,10]	2003	2007	151,588	168,634
Installation of diesel engines[6,10]	2017	2007	88,000	69,420
Transportation of diesel engines[7,10]	2017	2007	6,454	5,091
Installation of solar PV system and BOS[8,10]	2017	2007	4,524,623	254,510
Transportation of solar PV system and BOS[9,10]	2017	2007	195,464	150,580
Installation of flywheel energy storage[5,10]	2003	2007	22,738	25,295

Note:
1. The price of the 4 diesel engines was sourced from a base model set from Penske Power System.
2. The price was estimated from the solar PV system equipment cost from sample projects by MPower.
3. The standard retail price of the inverters was sourced from SMA Australia.
4. The cost for the single axis tracker was referred to the cost of the fixed mount from MPower. This price is adjusted using data from BREE (2013).
5. The acquisition and installation costs of the flywheel energy storage were based from the US Department of Energy study on flywheel energy storage of MILCON energy project (Rossow, 2003).
6. The installation cost of the diesel engine is based on the price quoted by Penske Power System. This includes the cost associated with labour, machinery and tools. For a 1.2 MW project, the time it takes it to complete installation is between 2 to 3 months and the average installation cost for diesel power stations in Australia is 1,100 AUD per day.
7. According to Penske Power System, additional freight cost is included for transporting diesel engines outside Perth metro region. This was estimated using an online freight cost estimator (Freight Exchange Calculator).
8. The general installation cost that includes labour and machinery use according to MPower is around 10% of total solar PV system cost. The average installation cost estimated by BREE (2013) is equivalent to 17.65% of the acquisition cost. This study then uses a nominal 15% installation cost. Sensitivity analysis can be done to determine the effect of the installation cost on the total life cycle cost.
9. According to MPower, the transportation cost of solar PV system and BOS equipment requires additional freight cost. This was estimated using an online freight cost estimator (Freight Exchange Calculator).
10. This cost was discounted to convert the reference value to the present value considered (2007) using historical inflation rate from the Reserve Bank of Australia.
11. The acquisition cost of the solar PV system and BOS, which were estimated in 2017 are adjusted to the base year 2007 using cost adjustment factors. According to NREL (2013), the price of solar PV project gradually decreased by almost 60% from 2009 to 2016.
12. The net present value of each cost element was calculated per MWh of electricity supplied to the load.

Table D.3 Breakdown of the operation and maintenance cost for the hybrid system in Marble Bar

Cost Element	NPV in Base Year (AUD)
Diesel power production[1,6]	6,317,999
Routine maintenance of diesel engines[2,6]	144,971
Routine operation and maintenance of solar PV system and BOS[3,6]	123,133
Spare parts usage of solar PV system and BOS[4,6]	20,591
Routine maintenance of flywheel energy storage[5,6]	41,411
Spare parts usage of flywheel energy storage[5,6]	3,711

Note:

1. This consists of two cost sources: diesel consumption and spare parts replacement.
   The amount of diesel consumed every year for the entire life cycle was estimated using HOMER software. The indicative price of diesel used (132 cents per litre) was sourced from Recharge Petroleum. The additional cost of diesel transportation was included and this value range from a minimum of 0.18 cents per litre to a maximum of 0.60 cents per litre.
   The amount of engine oil and coolant used was estimated using HOMER software and MTU Friedrichshafen GmbH (2003). The indicative prices of the engine oil and coolant used were 5.60 AUD per litre and 10.36 AUD per litre.
2. The maintenance cost of the diesel engines was sourced from DESS Power in Western Australia and this cost covers the expenses for inspection, replacement, reconditioning and major overhauls. This has an average price of 9 AUD per MWh and this price is more likely to be the same in the next few years according to DESS Power.
3. The routine operation and maintenance cost of the solar PV system was estimated from the studies conducted in Australia and indexed for regional Western Australia (BREE, 2013; CO2CRC et al., 2015). This cost consists of labour expenses, panel washing, weed abatement and additional material and maintenance that includes civil works, preventive maintenance and corrective equipment maintenance. A cost of 30 AUD/kW/year to 41 AUD/kW/year were calculated. In order to eliminate underestimation of the O&M cost, 41 AUD/kW/year was used in the analysis. Further sensitivity analysis can be made to determine the effect of this cost element on the total life cycle.
4. This includes the replacement of the inverters once over the life cycle. The standard retail price of the inverters was sourced from SMA Australia, while its transportation was estimated using an online freight cost estimator (Freight Exchange Calculator).
5. The routine maintenance and replacement of the vacuum and bearing of the flywheel energy storage were based from the US Department of Energy study on flywheel energy storage of MILCON energy project (Rossow, 2003).
6. The future costs were discounted to the base year (2007) using a 9% rate and summed to calculate their present values.

Table D.4 Breakdown of the life cycle cost of the improved RAPS options for the hybrid system in Marble Bar (FU = 1 MWh of electricity generation)

Cost Elements (NPV)	MB1	MB2	MB3	MB4	MB5	MB6	MB7	MB8	MB9	MB10
Capital	**115.01**	**115.22**	**116.88**	**123.12**	**130.01**	**136.25**	**117.09**	**123.33**	**130.22**	**136.46**
Acquisition of diesel engines	9.42	9.42	9.42	9.42	9.42	9.42	9.42	9.42	9.42	9.42
Acquisition of solar photovoltaic and balance of system	75.59	75.59	75.59	75.59	75.59	75.59	75.59	75.59	75.59	75.59
Acquisition of flywheel energy storage	7.51	7.51	7.51	7.51	7.51	7.51	7.51	7.51	7.51	7.51
Installation of diesel engines	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09
Transportation of diesel generator	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Installation of solar photovoltaic and balance of system	11.34	11.34	11.34	11.34	11.34	11.34	11.34	11.34	11.34	11.34
Transportation of solar photovoltaic and balance of system	6.71	6.71	6.71	6.71	6.71	6.71	6.71	6.71	6.71	6.71
Installation of flywheel energy storage	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13
Acquisition cost of additional installed renewable energy capacity	0	0	1.87	8.11	15.00	21.24	1.87	8.11	15.00	21.24
Acquisition and installation of exhaust gas recirculation	0	0.21	0	0	0	0	0.21	0.21	0.21	0.21
Operation and Maintenance	**300.71**	**294.92**	**301.14**	**294.65**	**290.61**	**288.33**	**290.43**	**284.76**	**281.47**	**279.58**
Diesel power production	285.90	280.05	286.15	279.25	274.77	272.00	275.50	269.42	265.67	263.29
Routine maintenance of diesel engines	6.40	6.46	6.41	6.27	6.17	6.12	6.35	6.21	6.13	6.08
Routine operation and maintenance of solar photovoltaic and balance of system	5.49	5.49	5.49	5.49	5.49	5.49	5.49	5.49	5.49	5.49
Spare parts usage of solar photovoltaic and balance of system	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
Routine maintenance of flywheel energy storage	1.84	1.84	1.84	1.84	1.84	1.84	1.84	1.84	1.84	1.84
Spare parts usage of flywheel energy storage	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Routine maintenance of additional installed renewable energy capacity	0	0	0.16	0.71	1.26	1.81	0.16	0.71	1.26	1.81
Total LCC	**415.73**	**410.15**	**418.01**	**417.77**	**420.62**	**424.58**	**407.52**	**408.09**	**411.69**	**416.04**

Table D.5 Breakdown of the capital cost for the hybrid system in Yungngora

Cost Element	Reference Year	Base Year	Amount of Reference Year (AUD)	Amount of Base Year (AUD)
Acquisition of diesel engines[1,7]	2017	2014	228,637.50	219,297.46
Acquisition of solar PV system and BOS[2,8]	2017	2014	645,310.02	817,987.10
Installation of diesel engines[3,7]	2017	2014	75,075.00	72,008.12
Transportation of diesel engines[4,7]	2017	2014	6,355.86	6,096.22
Installation of solar PV system and BOS[5,7]	2017	2014	122,698.07	117,685.74
Transportation of solar PV system and BOS[6,7]	2017	2014	162,931.90	156,275.99

Note:

1. The price of the 4 diesel engines was estimated from the base model set MTU Detroit engines from Penske Power System.
2. The price was estimated from the solar PV system equipment cost from sample projects by MPower.
3. The installation cost of the diesel engine is based on the price quoted by Penske Power System. This includes the cost associated with labour, machinery and tools. For a 1.2 MW project, the time it takes it to complete installation is between 2 to 3 months and the average installation cost for diesel power stations in Australia is 1,100 AUD per day.
4. According to Penske Power System, additional freight cost is included for transporting diesel engines outside Perth metro region. This was estimated using an online freight cost estimator (Freight Exchange Calculator).
5. The general installation cost that includes labour and machinery use according to MPower is around 10% of total solar PV system cost. The average installation cost estimated by BREE (2013) is equivalent to 17.65% of the acquisition cost. This study then uses a nominal 15% installation cost. Sensitivity analysis can be done to determine the effect of the installation cost on the total life cycle cost.
6. According to MPower, the transportation cost of solar PV system and BOS equipment requires additional freight cost. This was estimated using an online freight cost estimator (Freight Exchange Calculator).
7. This cost was discounted to convert the reference value to the present value considered (2014) using historical inflation rate from the Reserve Bank of Australia.
8. The acquisition cost of the solar PV system and BOS, which were estimated in 2017 are adjusted to the base year 2014 using cost adjustment factors. According to NREL (2013), the price of solar PV project gradually decreased by almost 21% from 2014 to 2016.
9. The net present value of each cost element was calculated per MWh of electricity supplied to the load.

Table D.6 Breakdown of the operation and maintenance cost for the hybrid system in Yungngora

Cost Element	NPV in Base Year (AUD)
Diesel power production[1,5]	6,016,856
Routine maintenance of diesel engines[2,5]	123,519
Routine operation and maintenance of solar PV system and BOS[3,5]	51,568
Spare parts usage of solar PV system and BOS[4,5]	55,159

Note:

1. This consists of two cost sources: diesel consumption and spare parts replacement.
2. The amount of diesel consumed every year for the entire life cycle was estimated using HOMER software. The indicative price of diesel used (132 cents per litre) was sourced from Recharge Petroleum. The additional cost of diesel transportation was included and this value range from a minimum of 0.18 cents per litre to a maximum of 0.60 cents per litre.
3. The amount of engine oil and coolant used was estimated using HOMER software and MTU Friedrichshafen GmbH (2003). The indicative prices of the engine oil and coolant used were 5.60 AUD per litre and 10.36 AUD per litre.
4. The maintenance cost of the diesel engines was sourced from DESS Power in Western Australia and this cost covers the expenses for inspection, replacement, reconditioning and major overhauls. This has an average price of 9 AUD per MWh and this price is more likely to be the same in the next few years according to DESS Power.
5. The routine operation and maintenance cost of the solar PV system was estimated from the studies conducted in Australia and indexed for regional Western Australia (BREE, 2013; CO2CRC et al., 2015). This cost consists of labour expenses, panel washing, weed abatement and additional material and maintenance that includes civil works, preventive maintenance and corrective equipment maintenance. A cost of 30 AUD/kW/year to 41 AUD/kW/year were calculated. In order to eliminate underestimation of the O&M cost, 41 AUD/kW/year was used in the analysis. Further sensitivity analysis can be made to determine the effect of this cost element on the total life cycle.
6. This includes the replacement of the inverters once over the life cycle. The standard retail price of the inverters was sourced from SMA Australia, while its transportation was estimated using an online freight cost estimator (Freight Exchange Calculator).
7. The future costs were discounted to the base year (2014) using a 9% rate and summed to calculate their present values.

Table D.7 Breakdown of the life cycle cost of the improved RAPS options for the hybrid system in Yungngora (FU = 1 MWh of electricity generation)

Cost Elements (NPV)	Yg1	Yg2	Yg3	Yg4	Yg5	Yg6	Yg7	Yg8	Yg9
Capital	**41.48**	**41.73**	**59.36**	**77.76**	**43.59**	**51.10**	**58.10**	**65.58**	**73.06**
Acquisition of diesel generator	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55
Acquisition of solar photovoltaic and balance of system	24.42	24.42	24.42	24.42	24.42	24.42	24.42	24.42	24.42
Installation of diesel generator	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15
Transportation of diesel generator	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Installation of solar photovoltaic and balance of system	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51
Transportation of solar photovoltaic and balance of system	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67
Acquisition and installation of exhaust gas recirculation	0	0.25	0	0	0	0	0	0	0
Acquisition cost of integrated utility-connected rooftop solar PVs	0	0	17.87	36.27	0	0	0	0	0
Acquisition cost of additional installed renewable energy capacity	0	0	0	0	2.11	9.62	16.62	24.10	31.58
Operation and Maintenance	**185.19**	**175.94**	**167.25**	**149.64**	**182.74**	**172.81**	**166.05**	**160.87**	**157.53**
Diesel consumption	178.35	169.06	160.78	143.52	175.82	165.57	158.42	152.83	149.03
Routine maintenance of diesel generator	3.66	3.69	3.29	2.93	3.61	3.39	3.24	3.13	3.06
Routine operation and maintenance of solar photovoltaic and balance of system	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54
Spare parts usage of solar photovoltaic and balance of system	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
Routine maintenance of additional installed renewable energy capacity	0	0	0	0	0.13	0.66	1.20	1.73	2.26
TOTAL LCC	**226.67**	**217.67**	**226.61**	**227.39**	**226.33**	**223.91**	**224.15**	**226.45**	**230.60**

Table D.7 continuation

Cost Elements (NPV)	Yg10	Yg11	Yg12	Yg13	Yg14	Yg15	Yg16	Yg17	Yg18	Yg19
Capital	**61.72**	**69.23**	**76.23**	**83.70**	**91.19**	**80.12**	**87.63**	**94.63**	**102.10**	**109.59**
Acquisition of diesel generator	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55	6.55
Acquisition of solar photovoltaic and balance of system	24.42	24.42	24.42	24.42	24.42	24.42	24.42	24.42	24.42	24.42
Installation of diesel generator	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15
Transportation of diesel generator	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Installation of solar photovoltaic and balance of system	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51
Transportation of solar photovoltaic and balance of system	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67	4.67
Acquisition and installation of exhaust gas recirculation	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Acquisition cost of integrated utility-connected rooftop solar PVs	17.87	17.87	17.87	17.87	17.87	36.27	36.27	36.27	36.27	36.27
Acquisition cost of additional installed renewable energy capacity	2.11	9.62	16.62	24.10	31.58	2.11	9.62	16.62	24.10	31.58
Operation and Maintenance	**149.26**	**142.21**	**138.06**	**135.48**	**134.08**	**138.42**	**133.89**	**131.31**	**130.06**	**129.49**
Diesel consumption	142.76	135.35	130.77	127.73	125.84	132.26	127.31	124.25	122.51	121.42
Routine maintenance of diesel generator	3.18	3.01	2.91	2.84	2.79	2.84	2.74	2.68	2.64	2.62
Routine operation and maintenance of solar photovoltaic and balance of system	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54	1.54
Spare parts usage of solar photovoltaic and balance of system	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65
Routine maintenance of additional installed renewable energy capacity	0.13	0.66	1.20	1.73	2.26	0.13	0.66	1.20	1.73	2.26
TOTAL LCC	**210.98**	**211.44**	**214.29**	**219.19**	**225.27**	**218.54**	**221.53**	**225.94**	**232.17**	**239.08**

Table D.8 Breakdown of the capital cost for the hybrid system in Coral Bay

Cost Element	Reference Year	Base Year	NPV in Reference Year (AUD)	NPV in Base Year (AUD)
Acquisition of diesel engines[1,6]	2017	2006	469,000	361,304
Acquisition and installation of wind turbine generator[2,7]	2009	2006	3,397,129	3,397,129
Acquisition of flywheel energy storage[3,6]	2003	2006	151,588	165,162
Installation of diesel generator[4,6]	2017	2006	154,000	118,637
Transportation of diesel generator[5,6]	2017	2006	1,725	1,329
Installation of flywheel energy storage[3,6]	2003	2006	22,738	24,774

Note:

1. The price of the 7 diesel engines was sourced from a base model set from Penske Power System.
2. The cost of the wind turbine generator was estimated from actual case study sites, which used wind turbines of same technical specifications (200 kW to 300 kW Enercon 33 turbine (GHD, 2009) and 200 kW to 300 kW GEV MPC turbine (Kanono & Aukitino, 2012)). The total acquisition cost includes the cost of turbines, the balance of plants (foundation, grid connection), engineering, shipping and installation.
3. The acquisition and installation costs of the flywheel energy storage were based from the US Department of Energy study on flywheel energy storage of MILCON energy project (Rossow, 2003).
4. The installation cost of the diesel engine based on the price quoted by Penske Power System includes the cost associated with labour, machinery and tools. For a 1.2 MW project, the time it takes it to complete installation is between 2 to 3 months and the average installation cost for diesel power stations in Australia is 1,100 AUD per day. Analogous cost estimation was done to estimate the cost of installing diesel engines in Coral Bay.
5. According to Penske Power System, additional freight cost is included for transporting diesel engines outside Perth metro region. This was estimated using an online freight cost estimator (Freight Exchange Calculator).
6. This cost was discounted to convert the reference value to the present value considered (2006) using historical inflation rate from the Reserve Bank of Australia.
7. The worldwide price of wind turbine has been consistently high until 2008/09 and this gradually decreases by almost 45% from 2008/09 to 2015 (US DOE, 2013). Therefore, the estimated wind turbine acquisition and installation cost in the year 2009 was not adjusted to the base year 2006.
8. The net present value of each cost element was calculated per MWh of electricity supplied to the load.

Table D.9 Breakdown of the operation and maintenance cost for the hybrid system in Coral Bay

Cost Element	NPV in Base Year (AUD)
Diesel power production[1,5]	7,917,580
Routine maintenance of diesel engines[2,5]	169,7267
Routine operation and maintenance of wind turbine generator[3,5]	371,783
Routine maintenance of flywheel energy storage[4,5]	37,692
Spare parts usage of flywheel energy storage[4,5]	3,112

Note:

1. This consists of two cost sources: diesel consumption and spare parts replacement.
   The amount of diesel consumed every year for the entire life cycle was estimated using HOMER software. The indicative price of diesel used (138.9 cents per litre) was sourced from Refuels Australia. The additional cost of diesel transportation was included and this value range from a minimum of 0.18 cents per litre to a maximum of 0.60 cents per litre.
   The amount of engine oil and coolant used was estimated using HOMER software and MTU Friedrichshafen GmbH (2003). The indicative prices of the engine oil and coolant used were 5.60 AUD per litre and 10.36 AUD per litre.
2. The maintenance cost of the diesel engines was sourced from DESS Power in Western Australia and this cost covers the expenses for inspection, replacement, reconditioning and major overhauls. This has an average price of 9 AUD per MWh and this price is more likely to be the same in the next few years according to DESS Power.
3. The routine operation and maintenance cost of the wind turbine system was estimated (49.37 AUD/kW/yr) from a study conducted in Australia and indexed for regional Western Australia (BREE, 2013). This cost is inclusive of turbines and all balance of plants, labour, facilities and equipment usage, spare parts and consumable replacement. There is a conflicting trend in the O&M cost from wind as evidence from the literature suggests both significant decrease and increase in O&M (BREE, 2013; GWEC, 2015, 2016; IEA, 2015; US DOE, 2016). This study then assumed a constant operation and maintenance cost for the entire life cycle. Further sensitivity analysis can be made to determine the variation of this cost element to the total life cycle using an O&M price that ranges between 22 AUD/kW/yr and 110 AUD/kW/yr (Synergy Australia).
4. The routine maintenance and replacement of the vacuum and bearing of the flywheel energy storage were based from the US Department of Energy study on flywheel energy storage of MILCON energy project (Rossow, 2003).
5. The future costs were discounted to the base year (2006) using a 9% rate and summed to calculate their present values.

Table D.10 Breakdown of the life cycle cost of the improved RAPS options for the hybrid system in Coral Bay (FU = 1 MWh of electricity generation)

Cost Elements (NPV)	CB1	CB2	CB3	CB4	CB5	CB6
Capital	**160.95**	**161.25**	**169.53**	**177.77**	**169.83**	**178.06**
Acquisition of diesel engines	14.29	14.29	14.29	14.29	14.29	14.29
Acquisition and installation of wind turbine generator	134.40	134.40	134.40	134.40	134.40	134.40
Acquisition of flywheel energy storage	6.53	6.53	6.53	6.53	6.53	6.53
Installation of diesel engines	4.69	4.69	4.69	4.69	4.69	4.69
Transportation of diesel engines	0.05	0.05	0.05	0.05	0.05	0.05
Installation of flywheel energy storage	0.98	0.98	0.98	0.98	0.98	0.98
Acquisition and installation of exhaust gas recirculation	0	0.30	0	0	0.30	0.30
Acquisition cost of integrated utility-connected rooftop solar PVs	0	0	8.58	16.82	8.58	16.82
Operation and maintenance	**334.95**	**328.55**	**329.68**	**323.72**	**322.08**	**316.42**
Diesel power production	311.92	305.22	306.64	300.68	299.04	293.38
Routine maintenance of diesel engines	6.71	6.71	6.71	6.71	6.71	6.71
Routine operation and maintenance of wind turbine generator	14.71	14.71	14.71	14.71	14.71	14.71
Routine maintenance of flywheel energy storage	1.49	1.49	1.49	1.49	1.49	1.49
Spare parts usage of flywheel energy storage	0.12	0.42	0.12	0.12	0.12	0.12
TOTAL LCC	**495.91**	**489.80**	**499.21**	**501.48**	**491.91**	**494.48**

Appendix E

Table E.1 Preliminary and final portfolio positions of the existing and improved RAPS options in Marble Bar

Improved RAPS Option	Preliminary Position		Final Position	
	Environmental Impact	Cost	Environmental Impact	Cost
Existing RAPS	1.09	1.01	1.11	1.01
MB1	1.08	1.00	1.09	1.00
MB2	0.95	0.99	0.94	0.99
MB3	1.08	1.01	1.10	1.01
MB4	1.06	1.01	1.07	1.00
MB5	1.05	1.01	1.06	1.01
MB6	1.05	1.02	1.05	1.02
MB7	0.93	0.98	0.91	0.98
MB8	0.91	0.98	0.89	0.99
MB9	0.91	0.99	0.89	0.99
MB10	0.91	1.00	0.89	1.00

Figure 5.1 shows the eco-efficiency portfolio of both the existing and improved RAPS options.

Table E.2 Eco-efficiency performance of improved RAPS options under different discount rates for the hybrid system in Marble Bar

Improved RAPS Option	Discount Rate		
	7.2%	**9%**	**10.8%**
MB1	-0.099	-0.094	-0.089
MB2	0.074	0.073	0.072
MB3	-0.112	-0.106	-0.101
MB4	-0.076	-0.074	-0.071
MB5	-0.067	-0.066	-0.064
MB6	-0.073	-0.073	-0.072
MB7	0.105	0.102	0.099
MB8	0.130	0.125	0.119
MB9	0.127	0.121	0.115
MB10	0.115	0.109	0.103

The improved options shaded in green are eco-efficient options, while the option shaded in orange is the most eco-efficient.

The eco-efficiency performance is measured as the distance of the portfolio positions to the diagonal line.

Table E.3 Eco-efficiency performance of improved RAPS options under different diesel prices for the hybrid system in Marble Bar

Improved RAPS Option	Diesel Prices (Cents Per Litre)		
	105.6	**132**	**158.4**
MB1	-0.096	-0.094	-0.092
MB2	0.079	0.073	0.068
MB3	-0.109	-0.106	-0.104
MB4	-0.077	-0.074	-0.071
MB5	-0.070	-0.066	-0.062
MB6	-0.079	-0.073	-0.068
MB7	0.108	0.102	0.097
MB8	0.130	0.125	0.120
MB9	0.125	0.121	0.119
MB10	0.111	0.109	0.108

The improved options shaded in green are eco-efficient options, while the option shaded in orange is the most eco-efficient.

The eco-efficiency performance is measured as the distance of the portfolio positions to the diagonal line.

Table E.4 Eco-efficiency performance of improved RAPS options with the imposition of carbon tax for the hybrid system in Marble Bar

Improved RAPS Option	With Carbon Tax	Without Carbon Tax
MB1	-0.095	-0.094
MB2	0.077	0.073
MB3	-0.108	-0.106
MB4	-0.076	-0.074
MB5	-0.069	-0.066
MB6	-0.077	-0.073
MB7	0.106	0.102
MB8	0.128	0.125
MB9	0.124	0.121
MB10	0.110	0.109

The improved options shaded in green are eco-efficient options, while the option shaded in orange is the most eco-efficient.

The eco-efficiency performance is measured as the distance of the portfolio positions to the diagonal line.

Table E.5 Preliminary and final portfolio positions of the existing and improved RAPS options in Yungngora

Improved RAPS Option	**Preliminary Position**		**Final Position**	
	Environmental Impact	**Cost**	**Environmental Impact**	**Cost**
Existing RAPS	1.57	1.02	1.79	1.02
Yg1	1.55	1.02	1.77	1.01
Yg2	1.33	0.98	1.46	0.98
Yg3	1.38	1.02	1.53	1.01
Yg4	1.21	1.02	1.29	1.02
Yg5	1.53	1.02	1.74	1.01
Yg6	1.41	1.01	1.57	1.00
Yg7	1.34	1.01	1.47	1.00
Yg8	1.28	1.02	1.39	1.01
Yg9	1.24	1.04	1.33	1.03
Yg10	1.12	0.95	1.16	0.96
Yg11	1.04	0.95	1.05	0.96
Yg12	0.99	0.96	0.99	0.97
Yg13	0.97	0.98	0.95	0.99
Yg14	0.95	1.01	0.93	1.01
Yg15	1.00	0.98	1.01	0.99
Yg16	0.94	1.00	0.92	1.00
Yg17	0.93	1.01	0.90	1.01
Yg18	0.91	1.04	0.88	1.03
Yg19	0.91	1.07	0.87	1.05

Figure 5.2 shows the eco-efficiency portfolio of both the existing and improved RAPS options.

Table E.6 Eco-efficiency performance of improved RAPS options under different discount rates for the hybrid system in Yungngora

Improved RAPS Option	**Discount Rate**		
	7.2%	**9%**	**10.8%**
Yg1	-0.787	-0.782	-0.777
Yg2	-0.450	-0.441	-0.432
Yg3	-0.542	-0.539	-0.537
Yg4	-0.304	-0.305	-0.305
Yg5	-0.751	-0.747	-0.742
Yg6	-0.582	-0.579	-0.576
Yg7	-0.474	-0.473	-0.471
Yg8	-0.399	-0.399	-0.399
Yg9	-0.355	-0.355	-0.356
Yg10	-0.127	-0.124	-0.119
Yg11	-0.019	-0.018	-0.015
Yg12	0.034	0.034	0.036
Yg13	0.058	0.058	0.058
Yg14	0.064	0.063	0.061
Yg15	0.006	0.008	0.009
Yg16	0.082	0.082	0.082
Yg17	0.090	0.089	0.087
Yg18	0.090	0.088	0.085
Yg19	0.079	0.076	0.072

The improved options shaded in green are eco-efficient options, while the option shaded in orange is the most eco-efficient.

The eco-efficiency performance is measured as the distance of the portfolio positions to the diagonal line.

Table E.7 Eco-efficiency performance of improved RAPS options under different diesel prices for the hybrid system in Yungngora

Improved RAPS Option	**Diesel Prices (Cents Per Litre)**		
	110.32	**137.9**	**166.48**
Yg1	-0.797	-0.782	-0.770
Yg2	-0.443	-0.441	-0.441
Yg3	-0.551	-0.539	-0.530
Yg4	-0.314	-0.305	-0.297
Yg5	-0.762	-0.747	-0.736
Yg6	-0.590	-0.579	-0.570
Yg7	-0.483	-0.473	-0.465
Yg8	-0.408	-0.399	-0.392
Yg9	-0.364	-0.355	-0.348
Yg10	-0.124	-0.124	-0.125
Yg11	-0.016	-0.018	-0.019
Yg12	0.036	0.034	0.033
Yg13	0.059	0.058	0.057
Yg14	0.063	0.063	0.062
Yg15	0.009	0.008	0.007
Yg16	0.085	0.082	0.080
Yg17	0.090	0.089	0.088
Yg18	0.088	0.088	0.088
Yg19	0.075	0.076	0.078

The improved options shaded in green are eco-efficient options, while the option shaded in orange is the most eco-efficient.

The eco-efficiency performance is measured as the distance of the portfolio positions to the diagonal line.

Table E.8 Eco-efficiency performance of improved RAPS options with the imposition of carbon tax for the hybrid system in Yungngora

Improved RAPS Option	With Carbon Tax	Without Carbon Tax
Yg1	-0.777	-0.782
Yg2	-0.443	-0.441
Yg3	-0.535	-0.539
Yg4	-0.300	-0.305
Yg5	-0.742	-0.747
Yg6	-0.575	-0.579
Yg7	-0.469	-0.473
Yg8	-0.395	-0.399
Yg9	-0.351	-0.355
Yg10	-0.126	-0.124
Yg11	-0.019	-0.018
Yg12	0.033	0.034
Yg13	0.057	0.058
Yg14	0.062	0.063
Yg15	0.007	0.008
Yg16	0.082	0.082
Yg17	0.089	0.089
Yg18	0.089	0.088
Yg19	0.077	0.076

The improved options shaded in green are eco-efficient options, while the option shaded in orange is the most eco-efficient.

The eco-efficiency performance is measured as the distance of the portfolio positions to the diagonal line.

Table E.9 Preliminary and final portfolio positions of the existing and improved RAPS options in Coral Bay

Improved RAPS Option	Preliminary Position		Final Position	
	Environmental Impact	Cost	Environmental Impact	Cost
Existing RAPS	1.09	1.00	1.09	1.00
CB1	1.08	1.00	1.08	1.00
CB2	0.95	0.99	0.95	0.99
CB3	1.05	1.01	1.06	1.01
CB4	1.02	1.01	1.02	1.01
CB5	0.92	0.99	0.91	0.99
CB6	0.89	1.00	0.89	1.00

Figure 5.3 shows the eco-efficiency portfolio of both the existing and improved RAPS options.

Table E.10 Eco-efficiency performance of improved RAPS options under different discount rates for the hybrid system in Coral Bay

Improved RAPS Option	Discount Rate		
	7.2%	9%	10.8%
CB1	-0.084	-0.079	-0.074
CB2	0.062	0.059	0.057
CB3	-0.065	-0.062	-0.059
CB4	-0.034	-0.033	-0.032
CB5	0.098	0.093	0.088
CB6	0.124	0.117	0.110

The improved options shaded in green are eco-efficient options, while the option shaded in orange is the most eco-efficient.

The eco-efficiency performance is measured as the distance of the portfolio positions to the diagonal line.

Table E.11 Eco-efficiency performance of improved RAPS options under different diesel prices for the hybrid system in Coral Bay

Improved RAPS Option	Diesel Prices (Cents Per Litre)		
	111.12	**138.9**	**166.68**
CB1	-0.081	-0.079	-0.077
CB2	0.064	0.059	0.056
CB3	-0.065	-0.062	-0.060
CB4	-0.037	-0.033	-0.030
CB5	0.097	0.093	0.090
CB6	0.120	0.117	0.114

The improved options shaded in green are eco-efficient options, while the option shaded in orange is the most eco-efficient.

The eco-efficiency performance is measured as the distance of the portfolio positions to the diagonal line.

Table E.12 Eco-efficiency performance of improved RAPS options with the imposition of carbon tax for the hybrid system in Coral Bay

Improved RAPS Option	With Carbon Tax	Without Carbon Tax
CB1	-0.079	-0.079
CB2	0.058	0.059
CB3	-0.062	-0.062
CB4	-0.032	-0.033
CB5	0.092	0.093
CB6	0.116	0.117

The improved options shaded in green are eco-efficient options, while the option shaded in orange is the most eco-efficient.

The eco-efficiency performance is measured as the distance of the portfolio positions to the diagonal line.