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Renewable Energy Microgrids: Economic Evaluation and Decision Making for Government Policies

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Abstract

This paper presents an economic evalulation of renewable energy microgrids, including ready-to-use three economic performance indicators for the general public's reference because of two main motivations: 1) economics is a crucial success factor of an engineering system, 2) unlike conventional large grids, any individuals can be an owner of a microgrid. The three economic performance and sustainability indicators are life-cycle cost, economies of scale and net present value, using generalized renewable energy microgrid data derived from 24 worldwide projects. The investment cost and operating cost is calculated to be 2,135 USD/kW and 0.066 USD/kWh respectively, both figures being higher than those of pulverized-coal and natural gas. The economies of scale factor is 0.9, which means although savings can still be enjoyed, the effect of economies of scale is weak. Furthermore, the net present value calculation reveals that the investment in renewable energy microgrid is not a profitable one. Next, based on the economic performance indicators results, recommendations for government policy-making are provided. It is concluded that investment-based policies delivered by the governments may be more effective than production-based policies, however, the two could complement each other in order to form a welcoming and sustainable renewable energy microgrid market.

Keywords: Microgrid, Energy Economics, Government Policies

1 Introduction

Fossil fuels continue to dominate the energy market. However, investment in renewable energy has been catching up, growing from 45 billion USD to 270 billion USD between 2004 and 2014. Among most types of renewable energy technologies, wind (onshore and offshore) received almost 56% of the share of finance, solar energy received around 24%, and biomass, waste, and biofuels received 15.2% [1]. This rise in investment could in part be due to a general perception that new renewable energy generations, backed up by suitable energy management strategies, can outperform traditional generation [2]. Harnessing renewable energy has been an ongoing challenge because of its unstable supply, yet microgrids have been considered to be a solution for effectively managing renewable energy generators and could also reduce pollution and lower costs with the aid of energy storage systems and appropriate optimization [3]. Microgrids can generally comprise 20-

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25& of on-site renewable energy in terms of capacity, but given the right demand and supply conditions, a higher renewable energy proportion is also possible [4]. Owing to its small-scale nature, its application is not limited to specialized operation by professional grid owners, but can be implemented at commercial and residential building sites [5,6], meaning that the public is engaged as stakeholders in the electricity market than ever. Overall, the use of renewable energy microgrids seems to be an effective solution for tackling global warming by acting as a clean energy management scheme. In addition to its technological and environmental advantages, its economic performance equally deserves the public's attention. This study collects financial data from worldwide microgrid projects and investigates the economic performance of renewable energy microgrids by evaluating key performance indicators including life cycle costing, net present value, and economies of scale. Furthermore, based on the economic study results, this study provides decision making supports for developing government policies.

2 Literature Review

2.1 Renewable energy application in microgrids

It has been suggested that renewable energy generations should: be unaffected by international political situations, be unharmful to the environment, utilize infinite resources, be accessible to all class and geographies, and be affordable [7]. These criteria lead to consideration of a wide variety of parameters during renewable energy application decision making, including environmental protection, technology, economics, market maturity, an abundance of renewable energy, and reliability [8–10]. Determining the most appropriate renewable energy application, with consideration of, for example, energy source types and mixes, depends on how much weight is allocated to each of these parameters. For instance, case studies [7] have reported that although solar thermal system for providing hot water and space heating in buildings could be the most cost-effective option out of the studied renewable energy technology options, solar energy from PV panels and hybrid renewable energy systems could offer other benefits (higher efficiencies, technological feasibility) that could be similarly important. In other words, renewable energy application is a complicated concept which needs iteration and optimization of multiple factors to result in a fit-for-purpose system.

Microgrids can be seen as a way to connect a number of independent and heterogeneous renewable energy systems together to form a complex and dynamic integrated energy system, essentially a system of systems [11]. The simplified general structure of a microgrid comprises of generators (renewable or non-renewable), storage systems, and loads. It can operate in alternating current, direct current or a mix of both, with their respective pros and cons [12]. There are a number of applicable standards to microgrids, such as IEEE 1547 Criteria and requirements for interconnection of DERs with the main grid and EN 50160 Voltage characteristics of electricity supplied by public distribution networks. Yet due to its emerging popularity, a wide variety (in terms of generation source, capacity, grid connection, etc.) of microgrids are undergoing development and operating worldwide [13]. Nevertheless, despite the dynamic nature of renewable energy resources, with proper balancing and control, a complex renewable energy microgrid can deliver stable and satisfactory electricity and energy [14,15].

2.2 Sustainability benefits of renewable energy microgrids

The benefits of microgrids can be assessed using the three pillars of sustainability: social, environmental, and economical. For social benefits, microgrids, as a localized electrification solution, can provide electricity to remote areas, enhance energy security, and prevent blackouts [16]. In addition, microgrids are associated with other long-term social benefits, for instance increasing public awareness of energy saving and greenhouse gas emission reduction, and new research and electrification in underdeveloped areas [17]. Though given that renewable energy generation is often fluctuating, it may require sophisticated algorithm optimization to maximize the social welfare, [18].

Regarding environmental benefits, the current literature does not lack life cycle assessment and other environmental analysis of renewable energy generation and microgrids [19–24]. In general, the literature favors the environmental performance of renewable energy microgrids, with findings suggesting that the utilization of natural renewable resources can reduce environmental pollution, but also highlighting a few environmental burdens such as heavy metal emissions.

In the economic arena, with proper planning and management, microgrids can result in enhanced economic efficiency, resulting from reductions in costs such as transmission loss, interruption cost, fuel cost, and emission cost [25]. On the other hand, it is also suggested that distributed energy and storage systems exhibit high economic costs and therefore hinder the development of their application [26]. Such findings may be inconsistent because, unlike environmental life cycle assessment, there are no universal ISO standards that can be applied on life cycle costing, and the cost data is often not public due to commercial reasons. Overall, the above three pillars of sustainable development, including in the case of microgrids, are tightly interlinked and multi-disciplinary [27]. The following section will present several studies that have examined the economic performance of microgrids.

2.3 Existing economic studies

Microgrids have seen as challenging to commercially evaluate for several reasons. Firstly, a microgrid represents a series of assets and infrastructure that come from different value streams, and during operation, a microgrid may go through several phases (generation, control, independence) but these phases are not distinct and often overlap [4]. In addition, not all cost and benefits can be taken into account by investors because the cost and benefits may be associated with a broad range of stakeholders. As investors are usually preoccupied with technical benefits and financial returns, they may not consider the part of the costs and benefits which do not have a direct impact on them [28,29]. Few studies have successfully captured non-financial outcomes of microgrids such as improved air quality, and represent them in economic terms [30]. All these factors lead to difficulties in formulating a business case for microgrids.

Despite these hurdles, some studies indicate that microgrids could be a solution to current economic inefficiencies associated with conventional electrical grids [31,32]. However, the literature does not seem to have reached an agreement regarding the investment payback of renewable energy. It has been reported that the payback period of PV panels could be up to 14 years, which is considerably long and primarily due to high equipment cost. This financial hurdle is shared across many emerging green technologies [33]. A business plan was prepared for a 4kW microgrid in a rural area of Kenya which aimed to generate sufficient revenue to cover the maintenance and replacement of equipment for the grid, in addition to human costs and other operation costs. It was concluded that the microgrid was economically sustainable and would also be profitable after one year of operation [34]. On the other hand, another study [35] found that it could be difficult for microgrids to be economically attractive when there is an alternative to connect to the main grid. In addition, renewable energy may sometimes suffer from cost fluctuation due to technological breakthroughs, government policies, and changes in feedstock prices [36]. There are some studies attempting to optimize the use of renewable energy based on economics and energy performance. Such techno-economic optimization can be carried out by comprehensively considering load profiles, penetration, energy investment, renewable energy generation, storage capacity. The optimum may be based on a performance index such as energy returned on energy invested, energy payback time, investment payment time and net present value [37–39]. It is apparent that existing studies have different positions on the commercial viability of microgrid solutions.

2.4 International government policies on renewable energy and microgrids

Worldwide there are governments supporting the finance of microgrid projects [40,41]. [42] prepared a review of the impacts of government policies on microgrid economics. One of the main objectives of government policies is to help grid owners achieve economic efficiency, such as through minimizing capital costs and/or operating costs. A variety of policies can be implemented to achieve this objective. Taking Australia as an example, a renewable energy fund ($500 million) was set up on a 1:2 basis, in order to leverage over $1.5 billion towards having national energy needs met with 20% renewable energy by 2020 [43]. [44] suggested that support policies can be conceptualized in terms of four dimensions: resource-geographic, financial, institutional and ecological. The study also discussed major constraints in meeting renewable energy goals, such as the lack of interactions between technical experts and social scientists, and huge investments to promote renewable energy on a national level. Effective policy making also requires consideration of different stakeholders, across disciplines and social demography [45]. Similarly, [46–48] point out that the importance of a government exercising caution about the interactions between its policies and industrial development in order to ensure healthy and sustainable growth in the renewable energy sector.

Governments can jumpstart conversion to renewable energy use by rolling out policies that support a stable and commercially sizable market, and reduce barriers to entry in terms of costs, infrastructure and information [49]. [50] reported that renewable energy support can be categorized as either investment-based or production-based schemes (Figure 1). Investment-based schemes finance systems with particular consideration of installation capacity, while production-based schemes, including quantity-based approaches (such as purchase obligations and tradable green certificates) and price-based ones (such as feed-in-tariffs and power purchase agreements), support renewable energy based on the output, and thus are more related to the electricity commodity market. There are also other production-based policies such as levying carbon taxes that may help capture the negative externalities of non-renewable energy and in turn increase the price competitiveness of renewable energy [51]. The success rates of various support policies differ between countries. For instance, despite the economic potential of renewable energy is very high in Russia and support by its government, the growth of the sector remains low [52]. Besides, it is suggested that Mexico's government has not demonstrated serious engagement in promoting renewable energy deployment as little has been done to improve transport efficiency [53]. In the UK, a series of policies have been implemented to ensure that the wholesale electricity market can accommodate low-carbon generation in the pursuit of meeting the country's renewable targets without compromising supply security [54]. For oil-producing countries, even more, effort will be required from the government as the current energy generation option is considerably less expensive than the deployment of renewable energy [55]. In contrast, the Chinese government has achieved remarkable gains—the wind turbine installation growth rate has been increasing by 100% each year, and nine out of fifteen PV manufacturers worldwide are located in China [56].

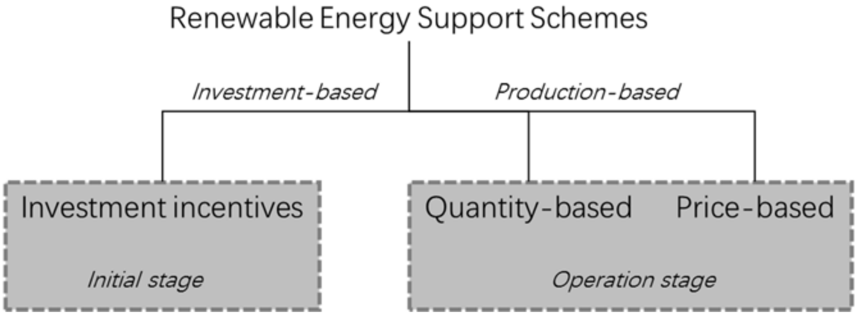

Figure 1 – Classification of Renewable Energy Support Schemes

3 Objective and significance

Unlike in traditional large-scale electricity generation (primarily coal and natural gas), where only the utility investors have to pay attention to grid economics, with microgrids any individual can be an investor given the small-scale and distributed nature of the technology. Although there are some costing studies on microgrids in the existing literature, they are mostly carried out for a single case study, producing results that are highly specific to that case's grid configuration and therefore of limited application to the planning of future projects.

The aim of the present study is to provide ready-for-use economic performance indicators of renewable energy microgrids to serve as a public reference. This study contributes to more effectively assessing microgrid adoption by generalizing 24 microgrid projects worldwide spanning different capacities and different levels of renewable energy adoption.

The generalized microgrid data is assessed based on three economic performance indicators to provide decision making support for investors (Table 1). Furthermore, based on the performance indicator results, this study offers suggestions to help government decision making in crafting policies to fund renewable energy efforts (Table 2).

Table 1 – Illustration of how the economic performance indicators can help investor decision making

Economic performance indicators	**Decision making support for grid investors**
Life cycle cost	Quantify the entry investment cost and the operating cost over the lifetime
Economies of scale	Evaluate the possibility of benefiting from savings by building larger capacity microgrids
Net present value	Understand the worthiness of investment considering the cash flow over time

Table 2 – Illustration of how the economic performance indicators can help government decision making

Economic performance indicators	**Decision making support for government policies**		
	Investment incentives	**Quantity-based**	**Price-based**
Life cycle cost	✓	✓	✓
Economies of scale	✓		
Net present value	✓	✓	✓

4 Proposed Methodologies

4.1 Case Study: 24 microgrid projects

Details for 24 microgrids worldwide were gathered from government and commercial reports [57–63]. Background information on these projects is provided in Table 3. In order to generalize the economic performance of renewable energy microgrid projects, the referenced projects must share one common feature which is the use of renewable energy in the grid at any capacity level. For a fair comparison, this study attempts to report results as unit cost, in terms of USD/kW capacity and USD/kWh energy output. Firstly, the background information of the microgrid projects is analyzed to produce generalized economic performance data on them. Secondly, 3 economic methodologies are employed to assess the performance and sustainability of the generalized case.

Table 3 – Background information on 24 microgrid projects worldwide, their capacity (total and renewable energy portion), and investment cost

The renewable energy microgrid projects	**Location**	**Year** [a]	**Capacity / kW**	**Renewable energy / kW**	**Investment Cost / USD** [b]
Santa Rita Jail Microgrid	Japan	2002	6,848	1,448	14,000,000
Isle of Eigg	UK	2008	266	166	2,124,800
L&T Chennai Campus	India	2009	1,820	138	2,000,000
Marble Bar and Nullagine	Australia	2010	1,580	300	3,577,000
San Diego Zoo Solar-to-EV Project	US	2012	190	190	1,000,000
Eagle Picher Power Pyramid ™ Demonstration	US	2012	1,030	30	2,628,000
2500 R Midtown Development	US	2013	281	77	850,000
Kansas Survival Condo	US	2013	450	100	800,000
Nagoya Landfill Microgrid	Japan	2014	700	500	1,500,000
US Marine Corps Base Camp Pendleton	US	2015	202	152	1,035,000
Alpha Omega Winery	US	2016	500	400	1,100,000
Ameren Distribution Microgrid	US	2016	1,475	225	5,000,000
Amtrak Sunnyside Yard microgrid	US	2016	18,200	200	31,300,000

The renewable energy microgrid projects	**Location**	**Year** [a]	**Capacity / kW**	**Renewable energy / kW**	**Investment Cost / USD** [b]
Shanghai Microgrid Demonstration	China	2017	206	156	371,400
The Thacher School	US	2017	1,000	1,000	4,330,000
Marcus Garvey Apartments	US	2017	1,100	800	3,000,000
OATI Microgrid Technology Center	US	2017	2,400	174	1,500,000
Peña Station NEXT	US	2017	2,600	1,600	10,300,000
Euroa Microgrid	Australia	2018	989	589	4,380,000
The Port of Long Beach Microgrid	US	2018	1,380	300	7,100,000
Singapore Renewable Energy Integration Demonstration	Singapore	2018	2,800	300	3,000,000
Miramar Naval Base	US	2018	7,000	1,600	20,000,000
Birchip Cropping Group Microgrid Demonstration	Australia	2019	188	51	232,870
Bornholm Island EcoGrid 2.0	Denmark	2019	112,500	35,500	14,700,000

Remarks:

a. Year refers to reported commissioned year or the year when the investment cost subject to how the reference is made available.
b. The investment cost shall be normalized to eliminate the price level change effect for analysis, an annual inflation rate of 2.5% is assumed. Exchange rates at the time of study are adopted (1 AUD:0.73 USD).

4.2 Life Cycle Costing (LCC)

Life cycle costing (LCC) has been proven to be an effective tool to assess the economic sustainability of energy systems. LCC addresses a system's economic performance over the entire life cycle, covering capital investment cost and operating costs such as operation, maintenance, and replacement [64]. Successful execution of LCC requires an adequate database and high transparency of cost data [65]. In this regard, the authors of this study made a diligent effort to gather the information required to perform the included analyses, and while assumptions are necessary, they are stated in relevant sections. Equation 1 represents the life cycle costs.

Equation 1 – Life cycle costing

$$\text{Life cycle cost} = \text{Capital costs} + \text{Lifetime operating costs}$$

While the investment costs of the renewable energy microgrid projects are already listed in Table 3, the operating cost of a microgrid depends on many factors, for instance, its type of generation, operation schedule, location, and level of automation [66]. Given that operating cost information for the projects included in this study is not available, the study alternatively estimates the operating cost as a percentage of capital cost. The previous microgrid LCC case studies report markedly divergent results: with operating costs as low as 1% of capital cost [67] up to 5-13% of capital cost [68–70]. This study assumes that the operating costs, including operation, maintenance, and replacement, is 10% of the investment cost. In addition, the capacity factor of renewable energy is assumed to be 0.3, and that of non-renewable energy is assumed to be 0.8 [71,72].

4.3 Economies of Scale

While making a commercial decision regarding renewable energy microgrid installation, the life cycle cost is not the only concern; whether an installation can benefit from economies of scale is also critical. The effect of savings due to economies of scale is usually measured by the economies of the scale factor. When the factor is smaller than 1, the cost per capacity keeps reducing as the capacity increases. The lower the factor is, the higher the economies of scale impact will be [73]. The economies of scale factor can be represented as shown in Equation 2.

Equation 2 – Economies of scale factor

$$\mathrm{C}_2 = \mathrm{C}_1 \left(\frac{\mathrm{S}_2}{\mathrm{S}_1}\right)^{\mathrm{n}} \qquad \mathrm{n} = \frac{\ln\left(\frac{\mathrm{C}_2}{\mathrm{C}_1}\right)}{\ln\left(\frac{\mathrm{S}_2}{\mathrm{S}_1}\right)}$$

C represents the cost of the plant and *S* represents the capacity of the plant. The subscripts *1* and *2* refer to the two respective systems to be evaluated. n is the economies of the scale factor. Note that in this particular section of the study, 3 outliers are not considered: the Isle of Eigg (outlier for relatively high investment cost per capacity), the Amtrak Sunnyside Yard microgrid, and the Bornholm Island EcoGrid 2.0 (outliers for relatively high capacity).

4.4 Net Present Value (NPV)

The investment worthiness of microgrids can be reflected by their net present value (NPV). NPV represents a discounted cash flow calculation, with the net cash flow discounted by a discount rate (interest rate) at a specific time, typically annually, and throughout the product's lifetime [74]. If the NPV over the lifetime is positive, the system is profitable, implying it is worthy of investment. In contrast, if the NPV is negative, the system is not profitable. Equation 3 is a standard formula for calculating NPV.

Equation 3 – Net present value

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{\text{Net cash flow}}{(1+i)^{t}}$$

n represents the system's life, *t* is the year, and *i* is the interest rate. To deduce the unit NPV (the NPV to provide 1 kWh each year), the investment costs and the capacities of microgrids are averaged. The net cash flow is the difference between the averaged global electricity price as derived from Figure 2 and the operating cost, an assumed 6% interest rate [75], and an assumed lifespan of 20 years. The NPV formula can be defined as shown below.

$$\mathrm{NPV}_{1\,\mathrm{kWh}} = \text{Investment cost}_{t=0,\ \text{capacity to generate 1kWh}} + \sum_{t=1}^{20} \frac{(\text{Electricity price}_{1\mathrm{kWh}} - \text{Operating cost of RE microgrid}_{1\mathrm{kWh}})}{(1+0.06)^{t}}$$

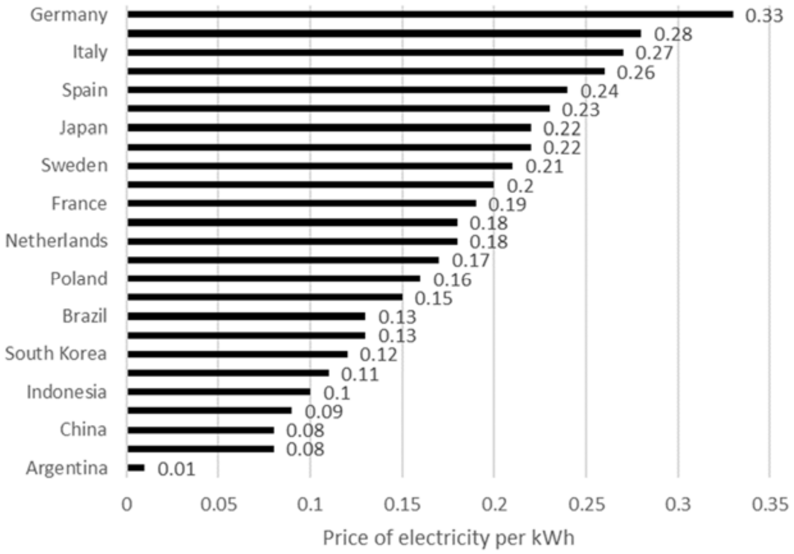

Figure 2 – Global Price of electricity per kWh in USD (2018) [76]

5 Results and Discussion

5.1 A dilemma between environmental and economic performance

Figure 3 shows the investment cost of a microgrid per installed capacity over their respective time spans of operation. With the cost normalized against inflation to eliminate the impacts of price level change, it can be observed that the investment cost per capacity gradually reduces with time. This could be due to the steady reduction in renewable energy cost in the last decade [77]. However, the commercial attractiveness of renewable energy microgrid investment cannot be easily determined by one parameter. Figure 4 presents the investment cost per capacity against the percentage of renewable energy capacity in a microgrid. The figure shows that the higher the renewable energy percentage is, the higher the investment will be required. It is commonly known that renewable energy is superior to non-renewable energy in terms of environmental performance. The findings in Figure 4 imply a dilemma between environmental performance and economic performance which is not often reported in the existing literature. The results of these two graphs indicate that despite the investment barrier shrinking over the past decade, harnessing the environmental benefits of renewable energy microgrids is still hindered by their steep investment costs.

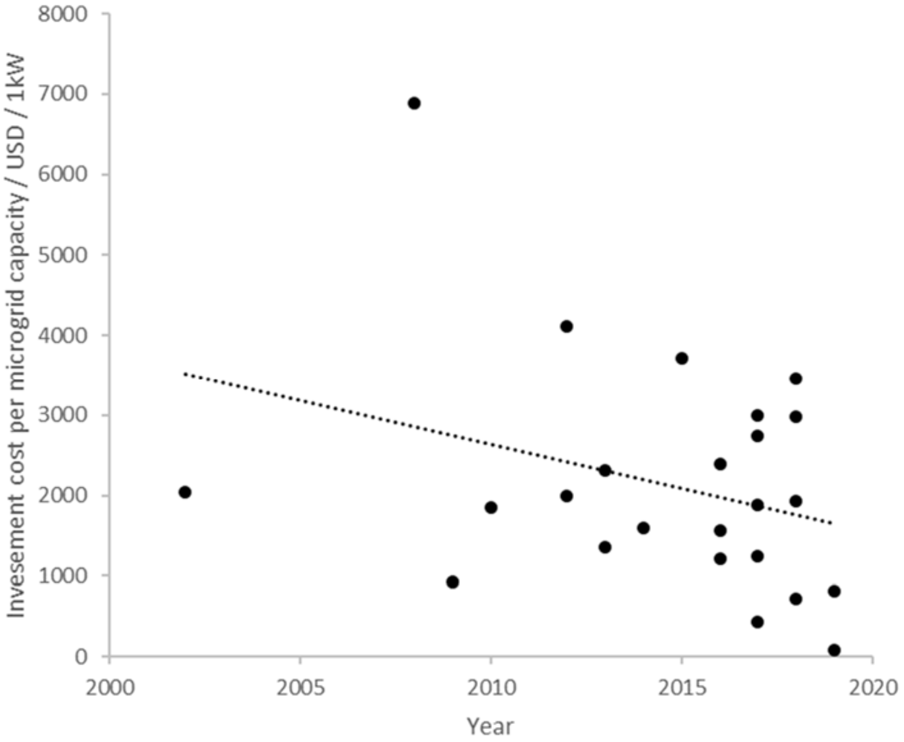

Figure 3 – Investment cost per microgrid capacity against time, with a linear trendline

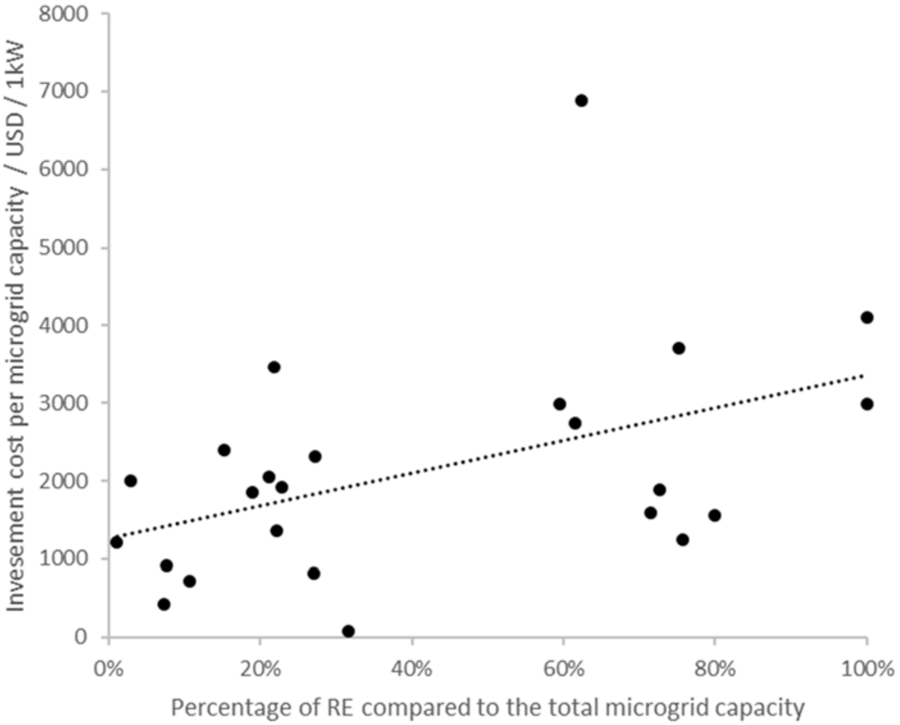

Figure 4 – Investment cost per microgrid capacity against renewable energy adoption, with a linear trendline

5.2 LCC: Investment Cost and Operating Cost

The life cycle cost of renewable energy microgrids consists of initial investment cost and operating costs. The investment cost is presented in USD/kW, in terms of installed capacity before operation commences. During the operation stage, the cost can be measured in USD/kWh, representing the unit cost of energy output. As a result, the investment cost and operating cost of a renewable energy microgrid are calculated to be 2,135 USD/kW and 0.066 USD/kWh respectively. These cost figures are compared to non-renewable energy power plants (Table 4). For investment cost, it is found that the capital needed to set up a renewable energy microgrid is higher than pulverized-coal combustion and natural gas combustion by 98% to 296% and 147% to 370%, respectively. Operating costs for a renewable energy microgrid are 0.55 to 2.3 times greater than for pulverized-coal combustion, thought these costs for a renewable energy microgrid are comparable to that for natural gas combustion (34% lower to 65% higher). Given the ongoing demand for clean energy and the gradual ruling out of coal combustion, the authors believe that the estimated renewable energy microgrid operating costs are bearable by investors.

Yet the more critical issue remains unsolved, as the investment cost of renewable energy microgrids creates a high market entry barrier and reveals significantly inferior price competitiveness compared to non-renewable energy electricity generation. As mentioned earlier, one of the essential principles of new energy generation is for it to be financially affordable to all parties, including investors and customers. The LCC results, in contrast, reveal that renewable energy microgrids still have not managed to reach a competitive level in the past decade. With reference to the trendline in Figure 3 and projecting the investment cost for another decade, renewable energy microgrids may begin to be price competitive with non-renewable energy generation in 2025, assuming there are no external factors such as significant technological breakthroughs or additional government interventions (Table 5). This finding suggests a 5-year delay for renewable energy's cost to undercut non-renewable energy's as compared to the suggestion in a renewable energy cost study [77] which suggested that renewable energy technologies could fall within the price range of fossil fuels by 2020.

Table 4 – Estimated investment cost and operating cost of renewable energy microgrid and other non-renewable energy power plants [71]

Technology	**Investment cost / USD/kW**	**Operating cost / USD/kWh**
Renewable energy microgrid	2,135	0.066
Pulverised-coal combustion	500 – 1,000	0.02 – 0.04
Natural gas combustion	400 – 800	0.04 – 0.10

Table 5 – Projection of renewable energy microgrid investment cost (2020 – 2029)

Year	**Investment cost / USD/kW**	**Year**	**Investment cost / USD/kW**
2020	1560	2025	1010
2021	1450	2026	900
2022	1340	2027	790
2023	1230	2028	680
2024	1120	2029	570

5.3 Implications of Economies of Scale

Graph depicting the economies of scale for the microgrid projects under study are shown in Figure 5 and Figure 6). Firstly, it can be observed that the investment cost per microgrid capacity non-linearly decreases as the capacity of the microgrid increases (Figure 5). This demonstrates some level of economies of scale taking place, meaning that the savings in terms of unit capacity can be enjoyed as the capacity is increased. Next, to quantify such savings, the data is mathematically analyzed with a natural log function. The gradient of the trendline in Figure 6 represents the economies of scale factor (EOS factor, *n*) which is computed to be 0.897 (or 0.9 when rounded to one significant figure). By definition, the closer to 1 the EOS factor is, the weaker the economies of scale will be, yet the product still benefits from related savings. Therefore, it can be interpreted that renewable energy microgrid projects exhibit weak economies of scale. Some literature has reported the EOS factors of various energy systems. It has been suggested that energy and chemical production plants generally have an EOS factor of 0.6 [78] and that coal generation features weak economies of scale [79]. Overall, such high EOS factors (though still lower than 1) can be considered as discouraging to investors to build renewable energy microgrids with considerable capacity. However, these EOS factors do not imply that there is no market potential for renewable energy microgrids at any capacity. For instance, a study on PV systems in Brazil [74] suggested that the market potential was strong particularly for small scale distributed systems.

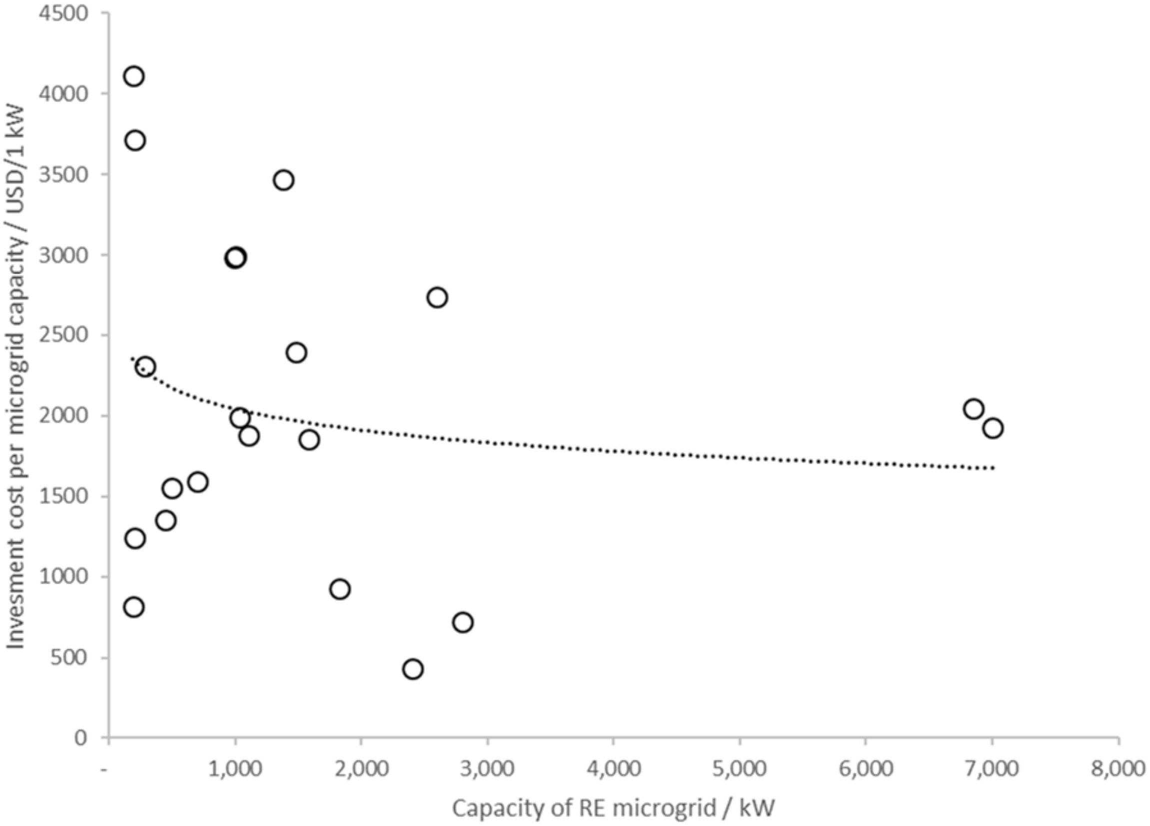

Figure 5 – Capacity of microgrid against investment cost per capacity, with logarithm trendline

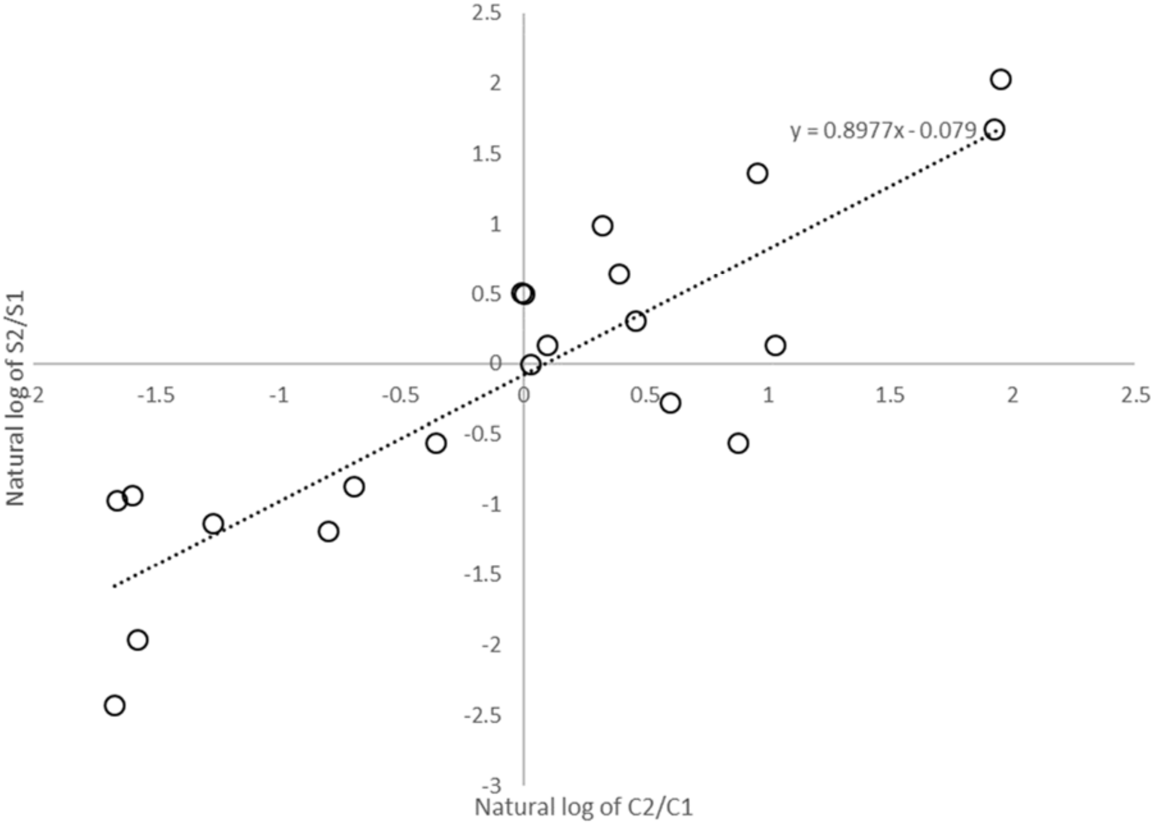

Figure 6 – Natural log graph to deduce the economies of the scale factor, with a linear trendline

5.4 Net Present Value

Table 6 shows the NPV calculation. The net cash flow is assumed to be the difference between electricity price (0.17 USD) and the operating cost (0.066 USD). From this table, three observations can be made. Firstly, the net cash flow during operation (20 years) is positive despite being discounted by the interest rate. This implies that renewable energy microgrid projects can be profitable during the operation stage. Secondly, as far as the NPV is concerned, the initial investment also has to be taken into account. As a result, the NPV does not become positive, despite the positive net cash flow during operation. Thirdly, by comparing the initial investment cost and the cash flow during operation, the difference in magnitude between the two is significant. It is highly unlikely that the operation revenue can cover the investment cost.

Considering these observations together, the economic sustainability of renewable energy microgrids is not encouraging. However, it is not uncommon to generate pessimistic economic sustainability results for renewable energy systems; two PV systems in the US were also reported to have negative NPV [80]. Another case study in Australia also concluded that the capital cost to run renewable energy is unaffordable and that climate change can only be effectively addressed on the supply side [81]. Yet the electricity price assumed in an NPV calculation can be limited because the electricity price may increase as the supply of fossil fuels faces shortage [82]. However as shown in the NPV calculation, the most apparent barrier to achieving positive NPV lies with the investment cost, and the electricity price charged during service has little impact on the NPV over the 20-year lifetime. Overall, it may be argued that a negative NPV should not be considered decisively disadvantageous, since current non-renewable energy technologies may also face the same problem. The deployment decision should not be based on solely commercial factors as renewable energy microgrids can generate social benefits such as energy security and reliability.

Table 6 – NPV calculation of renewable energy microgrid generating 1kWh (per year)

Year	**Net cash flow / USD/kWh**	**Year**	**Net cash flow / USD/kWh**
0 (Investment)	-2135.31	11	0.057
1	0.101	12	0.053
2	0.096	13	0.050
3	0.090	14	0.048
4	0.085	15	0.045
5	0.080	16	0.042
6	0.076	17	0.040
7	0.072	18	0.038
8	0.067	19	0.036
9	0.064	20	0.034
10	0.060	End of life	-2,134.08 (NPV)

As mentioned in Section 4.2, the operating cost can be 5 - 13% of the capital cost, thus a sensitivity test is carried out to reveal the impacts of this ratio on operating cost and net present value (Table 7). It is shown that within this ratio range, the impact on NPV is minimal because the net cash flow (electricity price minus operating cost) during operation is insignificant compared to the initial investment cost. This sensitivity test result echoes the previous suggestion that the investment cost is the major reason why microgrid may not be a worthwhile investment.

Table 7 – Sensitivity test for varying ratios of capital cost to operating cost

The ratio of capital cost to operating cost	**Operating cost / USD/kWh**	**NPV / USD**
1: 0.1	0.066	-2,134.08
1: 0.05	0.033	-2,133.70
1: 0.013	0.086	-2,134.31

5.5 Decision making support for government policies

This section provides decision making supports for government policies on renewable energy microgrids based on the three presented economic performance indicators. As mentioned in Section 2.4 and illustrated in Figure 1, government policies can be classified as investment-based, quantity-based, or price-based. It should be noted that investment-based policies focus on the initial stage, while quantity-based policies concentrate more on the operation stage.

Investment subsidy (Initial stage)

Based on the life cycle cost and net present value results, it is shown that the investment cost is significant compared to operating cost, and the investment is not paid back in 20 years. Therefore, it is apparent that the investment cost is the major hurdle for market entry. If a government wishes to encourage investors to participate in the microgrid market, it should deliver policies that can lower the barriers to entry, such as through subsidies. While this study compared the unit investment cost of renewable energy microgrid against traditional fossil fuel generations, it is recommended that a government subsidize the investment cost of a microgrid to a level comparable to these traditional means. Recapping the Australian case [43] mentioned in Section 2.4, it is possible that this 1:2 basis may create just enough incentive for investors to enter the market. This depends on the price competitiveness of renewable energy compared to fossil fuels, where for instance in oil-producing countries greater subsidies for renewable energy is required due to the abundant supply and lower price of oil.

Next, based on the economies of the scale factor, it is shown that renewable energy microgrids of large capacity may not be an attractive option for investors. Thus, it is recommended that if a government wishes to engage the public (any individuals), it may be more effective to first promote small-scale renewable energy installation, for instance, rooftop solar thermal systems or PV systems. Secondly, should a government wish to appoint investors to build large scale showcase renewable energy systems to raise public environmental awareness, it is proposed that the subsidy amount should increase with the capacity of the microgrid because investors may not enjoy economies of scale by building larger grids.

Quantity-based & price-based (Operation stage)

During the operation stage, a government can deliver quantity-based policies and price-based policies. Quantity-based policies can mandate electricity users to acquire a certain amount of electricity from renewable energy sources, and to mandate electricity providers to purchase tradable green certificates from renewable energy generators. Overall, quantity-based policies are pursued to help reach the targeted quantity of renewable energy generation. For price-based policies, such as feed-in-tariffs and purchase agreements, they set a price for renewable generations in the electricity market so that the generation becomes more cost-effective, or even profitable.

With reference to the life cycle cost and net present value results, two relevant points regarding operation can be recapped: 1) the operating cost of renewable energy is uncompetitive compared to coal but comparable to natural gas, 2) due to the high investment cost and little revenue generated, the investment does not pay itself back. While the gap in operating cost between renewable energy and fossil fuels is not as wide as the one in capital cost between the two, if a government wishes to financially support renewable energy operations, production-based policies may not be as effective as investment-based ones, however production-based policies are still necessary to maintain the price competitiveness and economic sustainability of renewable energy.

Complementary investment-based and production-based policies

Although it is suggested that investment incentives may be a more effective approach compared to production-based policies, a complementary implementation of the two policy types is essential because a singular focus on investment may lead to a compromise in quality and system efficiency, while a sole focus on production may not generate sufficient interest for investors to enter the market in the first place. Thus to create a welcoming and sustainable market for renewable energy microgrids, it is proposed that a government should first lower the barriers to entry by subsidizing the investment cost, then introduce production-based polices which can further promote the renewable energy microgrid market growth by supporting its commercial practicality.

5.6 Limitations

Constant electricity pricing in NPV calculation

This study assumes a constant (not time-varying) electricity price in the NPV calculation. Despite the rising popularity of real-time pricing and time-of-use pricing [42], such impact on the microgrid's economic performance is outside the scope of this study. It was reported that time-of-day pricing could, but not necessarily, improve the economics of microgrids, depending on whether net metering is allowed [83]. Another previous study [84] suggested that a high solar energy penetration (i.e., 33%) scenario does not necessarily lead to savings in electricity bills. It also depended on the pricing mechanism (time-of-use / real time) and whether hourly netting or net metering was adopted. The variation in changes in electricity bill was reported to be -25% to +7%. These studies demonstrate noticeable uncertainty remaining in generating savings through renewable energy and smart pricing.

Unaccounted externalities

While examining the sustainability of a microgrid, it is best that all costs and benefits that microgrids incur and bring are considered [85]. It has been suggested that investment in a microgrid can result in manifold benefits, such as enhanced energy efficiency and integrated renewable power generation. The benefits may also include greater balancing of supply and demand, cutting-edge security solutions to protect important infrastructure, and modular and operation-friendly solutions which may allow easy upgrade [75]. Even though these benefits are indeed commendable, not all these benefits can be straightforwardly quantified in economic terms and consequently can be overlooked during microgrid investment considerations. Therefore, non-renewable energy has the advantage of incurring low private costs although it imposes high social costs, while renewable energy suffers from high private costs although it exhibits high social benefits [86]. It is suggested that in future research sustainability net present value (SNPV) [87] can be adopted to comprehensively account for the economic, environmental, and social implications of various energy systems.

6 Conclusions

This study assesses the economic performance and sustainability of renewable energy microgrids, with the aim to assist investors' decision-making. In contrast to traditional electricity generation, anyone can be an investor in renewable energy microgrids due to their small-capacity and distributed nature. It is necessary to inform the public about the economic implications of renewable energy microgrids.

Data for 24 renewable energy microgrids installed worldwide was gathered and generalized to form the basis of this study. It is found that the investment costs of renewable energy microgrids have gradually declined over the last decade. In addition, a dilemma between environmental and economic performance is revealed as the investment cost of renewable energy microgrid increases with the percentage of renewable energy use. This represents difficulties in harnessing the environmental benefits of renewable energy. On the economic side, with the aid of LCC, the investment cost and operating cost of a renewable energy microgrid are calculated to be 2,135 USD/kW and 0.066 USD/kWh respectively. These cost figures are compared against non-renewable energy generation including pulverized-coal and natural gas, with renewable energy microgrid displaying inferior price competitiveness. In particular, the investment cost of a renewable energy microgrid is significantly higher than both forms of non-renewable energy generation, while the operating cost of a renewable energy microgrid is also significantly higher than coal, but it is comparable to natural gas. It is projected that by 2025 the costs of renewable energy microgrids will begin to be competitive with non-renewable energy generation. The implication of economies of scale is also studied. The EOS factor is calculated to be 0.9, which implies that the economies of scale is weak, but still takes place. Furthermore, the NPV calculation suggests that investment in a renewable energy microgrid is not a profitable one.

This study also provides decision making support for investment-based or production-based government policies based on economic performance indicators. It is suggested that due to the high market entry barriers, investment-based policies may be more effective compared to production-based policies. However, the two can complement each other in order to create a welcoming and sustainable renewable energy microgrid market.

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