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Key index framework for quantitative sustainability assessment of energy infrastructures in a smart city: An example of Western Sydney

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Abstract

Human society is experiencing a rapidly changing environment in which energy shortages and an ongoing climate crisis have been identified as two of the major challenges to the sustainable development of human civilization. In the face of these challenges, the concept of a smart city is proposed which aims at achieving sustainable development, increasing the quality of life, and improving the cost-effectiveness of existing and new energy infrastructures. To this end, this study proposes a general framework with a three-tier story chart for guiding the establishment of sustainability assessment models and the selection of their indicators. In addition, a quantitative analysis method is developed for assessing the sustainability of energy infrastructures in a smart city, which indicates how the long-term sustainability of the energy infrastructure can be achieved. The proposed method incorporates extensive environmental, economic, and social indicators, which go beyond conventional facility-level criteria and seamlessly relate to the broader community that benefits from the renewable energy transition (including energy construction, operations, and energy services). The proposed methodologies can be implemented through collecting the corresponding history data of the indicators and following the analysis procedures presented in this study. The proposed methodology can serve as a supporting tool for decision-making on new infrastructure investment and policymaking toward sustainable development. Case studies in Western Sydney were carried out to demonstrate the feasibility and efficiency of the proposed methodologies.

1 | INTRODUCTION

Sustainability represents a state of equilibrium between the social, environmental, and economic domains in the development of human beings. Sustainable development enables human beings to meet the needs of current generations without compromising the ability of future generations to fulfil their needs [1]. It has been widely recognized that sustainable development benefits society as a whole. In this context, sustainability assessment has become a significant task in guiding human activities in recent years.

Sustainability aims to achieve a good life for all human beings that is compatible with the ecological limits of living on a

finite planet. In the environmental domain, this means natural resources should be used prudently and human influence on natural ecosystems should be limited to the extent that planetary boundaries (the safe operating space of Earth systems) are not transgressed [2]. In the social domain, it means that basic needs and decent living conditions should be achieved for all individuals, poverty eliminated, inequality reduced in peaceful, inclusive, and just societies [3]. In the economic domain, sustainability means economic stability and financial security, inclusive and sustainable economic growth, full and productive employment, and decent work for all [4]. Economic growth (usually measured in terms of GDP) is often seen as an indicator of welfare, but this is being questioned by sustainability

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scientists who argue that health and subjective wellbeing are more important [5]. The definition of what is good depends on societal values and varies among countries over time.

In order to evaluate national or regional sustainability of development, numerous methodologies of sustainability assessment have been proposed in existing publications. In [6], an urban sustainability evaluation model was constructed to evaluate and compare the sustainability of 13 cities in the Beijing-Tianjin-Hebei region under different policy intervention scenarios. In [7], a hierarchical indicator system was established to evaluate the environmental governance and sustainability of urban industries in China. One of the main contributions in both [6] and [7] was that the impact of policies on the sustainability of regional development were measured in a quantitative way. In [8], an integrated assessment index framework was developed to address the aggregation of multiple key municipal aspects in the sustainability assessment of megacities. Notably, the United Nations sustainable development goals (SDGs) have been widely recognized among most countries and provide the best consensus to date of what a sustainable society should look like, covering economic, social, and environmental long-term aspirations. The annual SDG index and dashboard report provide national progress on SDG deliveries [9]. The high correlation between the SDG index and other existing sustainability indices was confirmed in [10]. Recent academic and expert literature as well as national experience in implementing the SDGs in 26 countries was reviewed in [11]. It was found that while progress has been made in some initial planning stages, key gaps remain regarding the assessment of interlinkages, trade-offs, and synergies between targets. Moreover, a multi-criteria analysis decision framework which assesses and prioritizes SDG targets in national implementation was proposed in [12].

Many frameworks and indices have been proposed at the city-level as well. The World Bank and the Global Environment Facility undertaken initiatives such as the Urban Sustainability Framework, the Global Platform for Sustainable Cities, the City Resilience Program, and the World Urban Forum. They have proposed key urban sustainability challenges including fiscal sustainability, social inclusiveness, economic competitiveness, low carbon footprints, and resilience. In the UK, the Sheffield Model adheres to the 'inclusive economy' principle and aims to build a city that is climate resilient, with affordable and sustainable energy for all, and to create inclusive economic growth. The U.S. Cities SDGs Index covers 49 indicators spanning 15 of the 17 SDGs across 100 of the most populated cities. Other influential city indices include the Global Power City index which encompasses the economy, R&D, and cultural interaction functions [13]. The Citizen Centric Cities 2018 focused on three pillars of sustainability, namely people, planet, and profit [14]. The City Momentum Index tracks a range of socioeconomic and commercial real-estate indicators to identify the expansion of business hubs [15]. In [16], a survey on schemes for sustainability assessment of smart cities was carried out to provide a typology of smart city assessment schemes. It should be noted that the issue of context is of particular importance in the selection of assessment methods and a scheme developed for a given city

will not necessarily be suitable for assessing other cities without making essential adjustments.

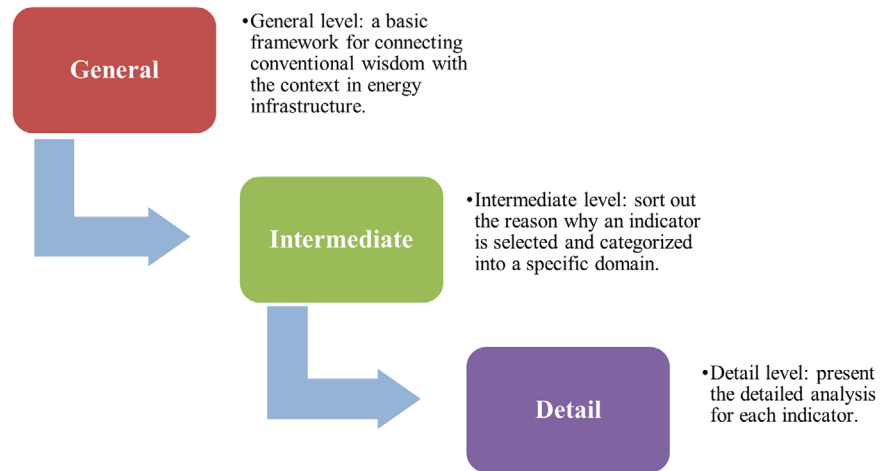
In the sustainability assessment of energy systems, [17] studied the sustainability of diverse electricity generation technologies using multi-criteria decision analysis, and provided a rank of these technologies based on their compatibility with the sustainable development of the industry. However, there were only ten sustainability indicators selected in the life-cycle analysis of power plants. In particular, a life-cycle sustainability assessment of electricity generation systems in Portugal, Tunisia, Greece, Northeast England, and Turkey were studied by [18–22], respectively.

Since sustainability is defined as a balance between the social, environmental, and economic domains, the existing sustainability assessment models for energy systems have been established by integrating a comprehensive range of indicators selected from environmental, economic, and social standpoints [23]. This has led to the multi-dimensional and complex nature of sustainability assessments, which usually calls for multi-criteria analyses (MCA) [24]. Sometimes, due to the incompleteness of the information and data, as well as the uncertainty in the sustainability evaluations, fuzzy logic has also been adopted [25].

Broad and comprehensive literature surveys on sustainability assessment methods adopted in energy systems have been carried out in [1,26, 27]. Comparative analysis of publications was systematically conducted for existing assessment methodologies. It has been found that a large number of methods with hundreds of sustainability indicators have already been developed. However, a general methodology to guide the establishment of a sustainability assessment framework and instruct the selection of sustainability indicators from the numerous candidate ones, is absent. Moreover, since the development of human society is featured by dynamic activities, sustainability assessment itself is dynamic. Therefore, continuous improvement of assessment indicators is needed considering the rapid development of smart cities.

Limitations of existing sustainability assessment methods can be observed in their practical application, including the ignoring of data availability (qualitative analysis is usually adopted when data is not available), the lack of general guidance on the establishment of a sustainability assessment framework for application in different regions, and insufficient correlation analysis between selected indicators and energy infrastructure development. As a result, the quantitative sustainability assessment outcomes obtained using existing assessment methods are less accurate and less credible when being used for the dynamic monitoring and evaluation of energy infrastructure sustainability. However, this study overcomes the above limitations of existing methods by establishing a generalized guidance framework for creating sustainability assessment models and conducting indicator selections. Meanwhile, a quantitative analysis method has been developed for dynamically monitoring and assessing the sustainability of energy infrastructures in a smart city. In particular, the proposed key index framework introduces a variety of indicators which measure the smartness of city development and this is a significant extension of existing

FIGURE 1 Philosophy behind the proposed three-tier story chart for indicator selection



sustainability assessment models. The main contributions of this study are summarized below.

Firstly, a general framework with a three-tier story chart is proposed for guiding the establishment of assessment models and the selection of indicators. Under the proposed methodology, indicator selection can be conducted using the same thinking process, which enables the proposed methodology to be applicable and transferable for sustainability assessment in other regions.

Secondly, a key index framework has been developed for the sustainability assessment of energy infrastructures in a smart city. The developed framework extends existing assessment indicators by incorporating those that measure the smartness of city development, such as the demand-side participation in energy systems, distributed battery energy storage systems, and the penetration level of electric transportation. The proposed methodology can help provide scientific evidence for decision-making on new infrastructure investment and policymaking toward sustainable development.

The rest of the article is structured as follows. Section 2 introduces details of the general methodology adopted in the proposed key index framework for sustainability assessment. Next, the rationale behind indicator selection is explained in Section 3. Numerical experiments and their corresponding results analysis are presented in Section 4. Finally, Section 5 concludes the article.

2 | GENERAL METHODOLOGY

2.1 | Selection of indicators in key index framework

Through the extensive survey of prevailing sustainability assessment frameworks, it was found that a large number of indicators have been developed through existing research for assessing the sustainability of energy systems. Users can select and customize a portfolio of these indicators based on the specific requirements of their application. However, general rules and guidance are still needed to help users make decisions on

their indicator selection. In order to implement and organize the key indicators for practical application, a three-tier story chart for indicator selection was developed in the proposed key index framework.

The first tier of this chart is at a general level and is used to provide a basic framework for connecting conventional wisdom with its context within the energy infrastructure. The second tier of the chart is at an intermediate level and is used to sort out the reason why an indicator is selected and categorized into a specific domain. The third tier of the chart is at a detailed level and presents a comprehensive analysis of each indicator. The logic behind the three-tier story chart is presented in Figure 1.

Table 1 presents the details of the general level ideas for indicator selection. In Table 1, the section of conventional wisdom and general feeling is the first step to establish a rational story for each indicator. It describes the broad and general context in each domain and does not focus on the energy-related context. The context in the energy infrastructure realm and energy-related descriptions are involved in the second step, where the energy-related context in each domain is elaborated upon to connect conventional wisdom with the energy infrastructure.

Then, in the intermediate level of indicator selection, each indicator can directly link with the general level analysis via a keyword (see Figures 2–4), as it defines which domain is reasonable for each indicator. Consequently, each indicator can be allocated to each domain by keyword, and some indicators may fall into multiple domains. The detailed rationale of indicator selection and the meanings of each indicator are demonstrated in Section 3.

At the detail level, in-depth analysis of each indicator can be carried out. Notably, all indicators are used to assess the sustainability of energy infrastructure in a smart city during its development toward a higher level of sustainability, and this is measured by the penetration of renewable energy (RE). In order to ensure the validity of the final sustainability assessment results, the correlation between the selected indicators and the RE scenarios should reach a certain level. If not, these indicators are unable to effectively reflect the change of sustainability. Currently, there are several commonly adopted correlation analysis methods,

TABLE 1 General level: the basic framework for connecting conventional wisdom with the context in energy infrastructure

Conventional wisdom and general sense			Context in the energy infrastructure	
General feeling from the perspective of economy, environment and society			Impact by energy infrastructure	
Domain	What is good? (sustainability criteria)	Impact factor	How energy infrastructure can contribute to the specific aspect?	Put keyword in each impact Keyword
Economy	Sustainable and stable economic growth	(i) Economic stability	(i) Cost-effectiveness in energy supply and related investment	(i) New investment
		(ii) General welfare and prosperity	(ii) Cost-effective integration of renewables into existing power system	(ii) Cost-effectiveness
	Less inequality	Energy price	(iii) No disturb economy by sustainable and stable energy resources and system operation	(iii) Stable economy
			(iv) Less cost fluctuation of electricity	(iv) Effective energy usage
Environment	Protection of natural environment	(i) Pollution emission	(i) Less pollution against environment	(i) Decent living cost /Economic growth
		(ii) Resource consumption	(ii) Less conventional fossil fuel based generation and more renewables	(ii) Effective energy usage
	Less risk against climate change	Greenhouse gas emission	(iii) Effective and sustainable resource use with integrating renewables	(iii) Less pollutant and pollution
			(iv) Less nature destruction and less impact on ecosystem	(iv) Effective resource usage
	Better living environment	(i) Landscape (ii) Area value	(i) Less greenhouse gas emission	(i) Support RE
			(ii) Less conventional fossil fuel based generation and more renewables	(ii) Nature damage
Society	Safe and healthy life	(i) Safety of life	(i) Less damage on landscape and area value	(i) Better landscape
		(ii) Health damage	(ii) Effective land use to the development of renewables	(ii) Effective land usage
	Convenient and happy life	(iii) Resilience of energy systems	(i) Stable energy supply and resilient system against disaster and accident	(i) Stable supply
		(i) Living standard	(ii) No occurrence in health damage and dangerous event	(ii) Safety and health
	Respect in freedom and privacy	No energy data usage without permission of customers	(iii) Less pollutant emission damaging human health	
			(ii) Equity	(i) Easy access and use to make life better
	and privacy preservation		(ii) Job opportunity related to energy system transition	(ii) Job opportunity
			(iii) Employment	(i) Less dependency on monopolized companies and more independency in energy selection
			(ii) More energy independence from the perspective of individuals and the whole society	(ii) Energy independence
			(i) Market competition	
			(ii) Independence of energy supply	
			(i) Human rights	
				Security of energy data
			(ii) Privacy preservation	

including the Pearson correlation, the Kendall rank correlation, the Spearman correlation, and the Point-Biserial correlation. Among these methods, the Pearson correlation is a measure that investigates the linear relationship between two continuous random variables. It does not assume normality although it assumes finite variances and finite covariance. However, the Kendall and Spearman methods are usually applied for ranking correlation analysis to obtain a measure of a monotonic relationship between two continuous random variables, while the Point-Biserial method was designed for correlation analysis when one

variable is dichotomous. Thus, considering that there are neither ranking nor dichotomous factors in this analysis, the Pearson correlation model was employed. Let ρ_i denote the correlation coefficient for the i^{th} indicator, and only indicators with a $|\rho_i| \geq 0.4$ are selected in the framework.

Furthermore, since it is unknown beforehand whether an indicator is positively or negatively correlated with the RE scenarios, various combinations of development trends between an indicator and the RE scenarios were considered in the correlation analysis (see Table 2). The final correlation coefficient for

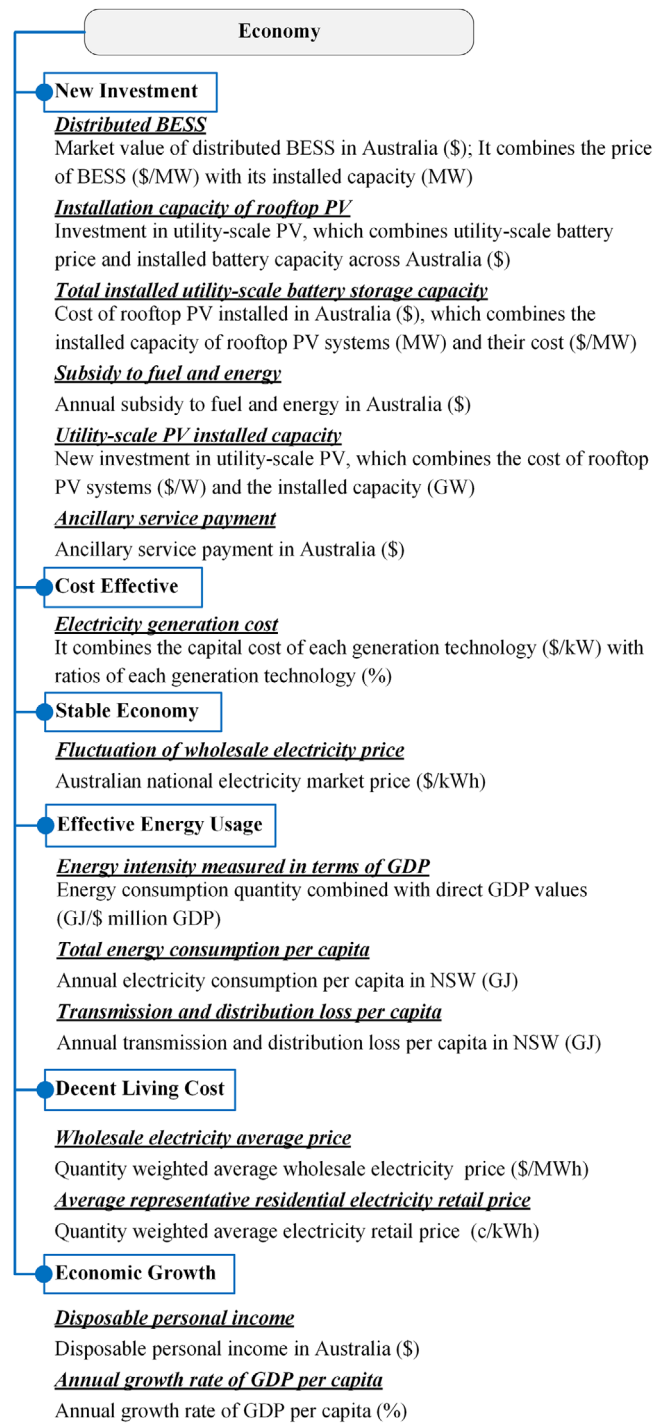


FIGURE 2 Indicator selection under each key word in the economy domain

each indicator was set as the average value of these results.

$$|\rho_i| = \sum_{m=1}^3 \sum_{n=1}^3 |\rho_{mn}| / 9 \quad (1)$$

In the developed three-tier story chart, indicator selection was conducted using the same thinking process presented in a

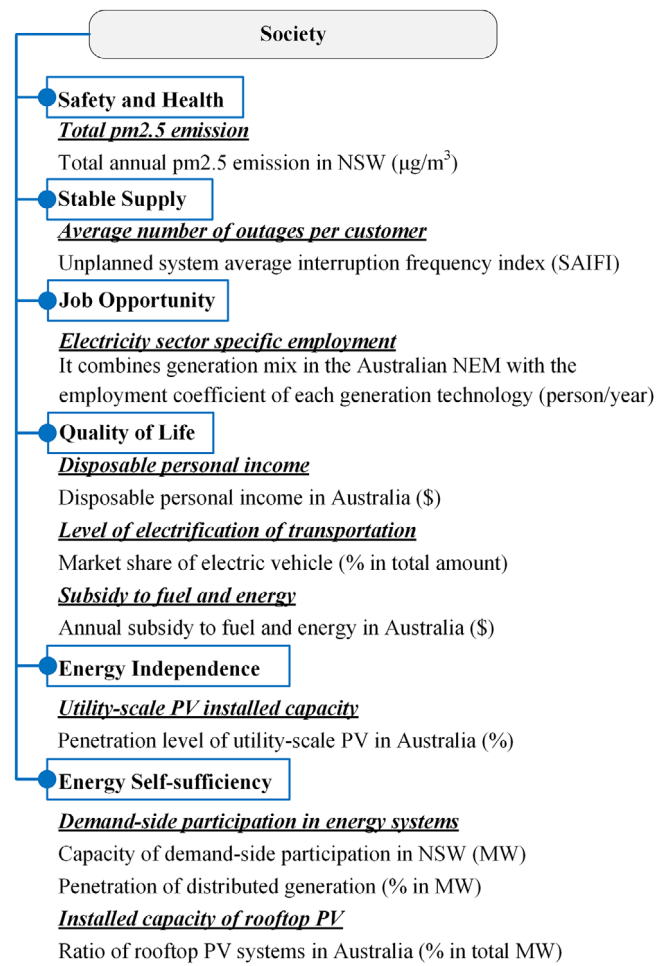


FIGURE 3 Indicator selection under each key word in the society domain

summarized way. It can become a useful guideline when considering other areas which enable the proposed methodology to be applicable and transferable in the assessment of the sustainability of energy systems in other regions.

2.2 | Forecasting of indicator future values

With long-term sustainability analysis in mind, the forecasting of indicators is necessary. Forecasting in engineering is a field that attracts extensive research interests. In power systems, various methods and models have been proposed and applied in the forecasting of electricity loads and prices. According to the different forecast lead times, forecasting techniques can be generally categorized into short-term and long-term techniques. For both the electricity load and price, the short-term approach refers to forecasting with a lead time of up to several weeks and is mainly conducted for short-term power system operations. By contrast, the long-term approach aims to forecast future values with a longer lead time of up to a few years and is mainly used for long term system planning [28].

The majority of existing publications have been focusing on short-term forecasting techniques (STF), and far fewer

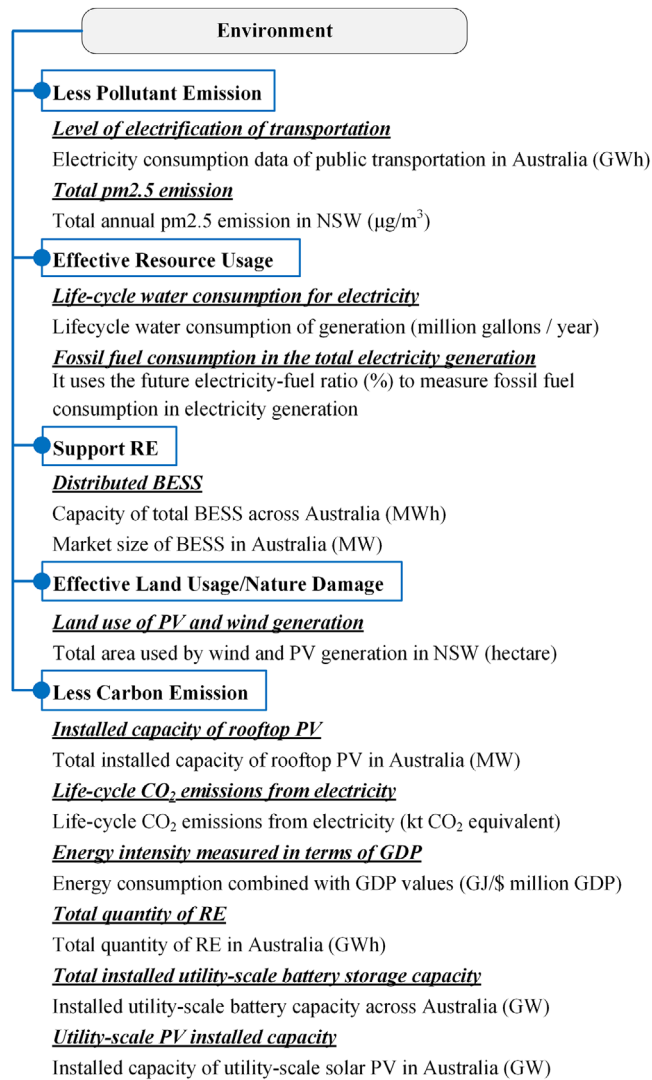


FIGURE 4 Indicator selection under each key word in the environment domain

TABLE 2 Correlation analysis of indicators

		Scenarios of RE		
		Low	Medium	High
Scenarios of indicator	Low	$ \rho_{11} $	$ \rho_{12} $	$ \rho_{13} $
	Medium	$ \rho_{21} $	$ \rho_{22} $	$ \rho_{23} $
	High	$ \rho_{31} $	$ \rho_{32} $	$ \rho_{33} $

research has been done on long-term forecasting (LTF). Artificial neural networks have been applied in many STF load forecasting approaches, including the extreme learning machine approach [29,30], the support vector regression [31], the time-varying autoregressive model [32], as well as the semi-parametric additive model [33]. Statistical time series models such as autoregressive (AR), moving average (MA), and autoregressive integrated moving average (ARIMA) can also be applied to prediction, especially when the problems are modelled on dis-

crete time series [34]. In [9], a comprehensive review of the evolution of energy forecasting practices was presented, starting from the time when Edison founded his steam-powered power station. Load forecasting approaches from the pre-PC era to the current smart grid era were also summarized.

In the forecasting of indicator future values, it is often an LTF problem rather than a STF one. Compared to STF problems, LTF is more challenging since there are many more uncertain factors over a long-term period. However, STF techniques can still be employed to solve LTF problems with minor modifications. For example, through adding a macroeconomic indicator which captures the long-term changing trend of electricity loads, multiple linear regression analysis was used for LTF in [35]. In addition, if there is no significant change in the evaluation pattern of indicators over the coming years, the STF models can be directly applied to LTF.

Furthermore, considering that there are usually tens of indicators in a typical sustainability assessment model, the availability of historical data for each indicator is an essential issue. Without sufficient historical data, some of the existing forecasting techniques may fail to work, especially artificial-intelligence-based methods. Therefore, in the proposed framework, the annual-growth-rate (AGR) and confidence-interval (CI) based methods were employed for indicator forecasting without sufficient historical data.

As has been observed, for some indicators, there are forecasting results released by official organizations, such as the AGR of gross domestic product (GDP) forecast by the International Monetary Fund. Consequently, for indicators with official forecasting AGR available from some or other agents, the AGR-based method is adopted for indicator forecasting, as given below.

$$V_j^{\text{indicator}} = (1 + \tau_j^{\text{AGR}}) \times V_{j-1}^{\text{indicator}} \quad (2)$$

where τ_j^{AGR} denotes the AGR of the indicator during year j , and $V_j^{\text{indicator}}$ is the indicator value at the end of year j .

For indicators without sufficient data to implement the above mentioned sophisticated STF and LTF methods, the CI-based method can be employed to estimate the upper and lower bounds of τ^{AGR} for the indicators. In statistics, CI is a method that can be used to estimate the range of plausible values for an unknown parameter from the statistics of observed data. It also has an associated confidence level which represents the probability that the unknown parameter falls into that interval. For a specific indicator, it can be assumed that its AGR in a certain year obeys a normal distribution $N(\mu, \sigma^2)$ where μ and σ denote the mean and standard deviation of the AGR, respectively. μ and σ can be derived using the limited historical data of indicators. It follows then, that the CI method is employed to estimate the range of indicator AGRs at a given confidence level, namely:

$$P(\tau^{\text{AGR,low}} \leq \tau^{\text{AGR}} \leq \tau^{\text{AGR,high}}) = 1 - \alpha \quad (3)$$

where $\tau^{\text{AGR,low}}$ and $\tau^{\text{AGR,high}}$, respectively, indicate the lower and upper bounds of τ^{AGR} at a confidence level $1 - \alpha$.

Consequently, values of $\tau^{AGR,low}$ and $\tau^{AGR,high}$ can be calculated as follows:

$$\tau^{AGR,high} = \tau^{AGR,med} + \xi_{1-0.5\alpha} \cdot \sigma^{indicator} \tag{4}$$

$$\tau^{AGR,low} = \tau^{AGR,med} - \xi_{1-0.5\alpha} \cdot \sigma^{indicator} \tag{5}$$

$$\xi_{1-0.5\alpha} = \Phi^{-1}(1 - 0.5\alpha) \tag{6}$$

$$\tau^{AGR,med} = \mu \tag{7}$$

where $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution and $\Phi^{-1}(\cdot)$ is its inverse function. $\xi_{1-0.5\alpha}$ is the intermediate variable.

Finally, after substituting $\tau^{AGR,low} / \tau^{AGR,med} / \tau^{AGR,high}$ as the indicator AGR into (2), the indicator forecasting values corresponding to the low, medium, and high scenarios can be derived, respectively.

2.3 | Calculation of indicator score

Before introducing the calculation of indicator score, the concept of the desired direction needs to be defined. The desired direction can be set by the decision-makers for later quantitative sustainability assessment, and it signifies the direction in which the indicator should change to achieve a higher level of sustainability. Under this method, when using indicators to assess the development toward higher sustainability, a larger score always implies superiority over a smaller score. For example, inequality should decrease to achieve higher economic sustainability, and hence its desired direction is set as negative. Meanwhile, the participation of demand-side response is expected to increase for a more sustainable energy system in the future. Consequently, its desired direction is positive. Therefore, an indicator with a negative desired direction will have a smaller score with a higher indicator value, and vice versa. For indicators with negative and positive directions, their indicator scores are calculated using (8) and (9), respectively.

$$r^{negative} = \frac{V^{target}}{V^{actual}} \tag{8}$$

$$r^{positive} = \frac{V^{actual}}{V^{target}} \tag{9}$$

where V^{target} denotes the target value of the indicator and V^{actual} represents the actual indicator value. $r^{negative}$ and $r^{positive}$ are the scores of indicators with negative and positive directions, respectively.

Under the above calculation method, when using indicators to assess the development toward higher sustainability, a larger score always implies superiority over a smaller score. As previously mentioned, various indicators belonging to the same domain are used to comprehensively assess the sustainability

of energy infrastructures during the development of a smart city toward a higher penetration of RE. In order to leverage the impact of individual indicator scores on the overall score of their sustainability domain, weighting factors have been applied in this framework. The weighting factors for an indicator in a specific domain can be derived with Equation (10).

$$w_i = \frac{1}{N^{domain}} \tag{10}$$

where w_i indicates the assigned weighting factor for the i^{th} indicator in a specific domain; and N^{domain} is the number of indicators in this domain.

Therefore, for each of the economy, environment, and society domains, the score is calculated as follows:

$$R^{domain} = \sum_{i=1}^{N^{domain}} w_i r_i \tag{11}$$

where R^{domain} is the score of a specific domain; and r_i is the score of indicator i .

3 | RATIONALE OF INDICATOR SELECTION

This section provides brief descriptions of why each indicator in Figures 2–4 is of particular importance to constitute the proposed key index framework, as well as the setup of indicator desired directions for the aforementioned indicator score evaluation.

1. **Demand-side participation (DSP) in energy systems:** With the establishment of electricity markets, the rise of smart consumers, and the growth of distributed RE generation, demand-side is becoming a flexible power source in power systems. DSP is a core component of demand-side management (DSM) that refers broadly to the active change of usual or baseline electricity consumption in response to changing electricity industry conditions. Therefore, a growing DSP should be considered to increase the flexibility of power grids, which will help improve the accommodation of renewable generation in power systems. The desired direction for this indicator is POSITIVE.
2. **Distributed battery energy storage system (BESS):** A BESS integrates energy production and consumption on the user-side and has gradually become an indispensable part of modern power systems. In this context, the increasing penetration of distributed RE sources needs a corresponding BESS to provide support because of its intermittent characteristic. Additionally, the development of a BESS also serves the utilities. For example, smart dispatch of a virtual power plant can satisfy application requirements such as frequency control, peak shaving, as well as energy shifting, and voltage control. Therefore, the indicator of

- a distributed BESS should be considered when evaluating energy systems. The desired direction for this indicator is POSITIVE.
3. **Wholesale electricity average price:** Wholesale electricity in eastern and southern Australia is traded through the national electricity market (NEM), a spot market in which supply and demand conditions determine prices in real time. Over 200 large-scale power stations sell electricity into the market, which is transported along 43,000 km of transmission lines to almost 10 million energy consumers [36]. The energy market is rapidly evolving with wind and solar generation replacing retiring coal-fired power generators in the market. By January 2020, over 2 million Australian energy customers had become energy producers by installing rooftop solar photovoltaic (PV) systems, and many of them are sending surplus production back into the grid. These systems accounted for approximately 5 per cent of the total energy requirements in the NEM in 2019. Moreover, the volatility of wholesale electricity prices directly reflects the economic stability of the electricity market. Therefore, the indicator of wholesale electricity average price should be considered when evaluating energy systems. The desired direction for this indicator is NEGATIVE.
 4. **Average representative residential electricity retail prices:** In the Australian NEM, the increasing rate of electricity and gas prices is expected to moderate in most states and territories over the next few years, after a period of significant increases. However, intergovernmental agreements and action by the state and territory governments are the most important policy levers to curb future price increases. Thus, electricity retail prices will continue to increase. The underlying cause of these increases is different for electricity and gas, and the contribution of each factor is also different for each state and territory. Therefore, the indicator of national average representative residential retail electricity prices should be considered when evaluating energy systems. The desired direction for this indicator is NEGATIVE.
 5. **Disposable personal income (DPI):** DPI is one of the economic indicators commonly used to reflect living standards and general economic status. Considering the progress in power systems, changes in electricity demand and other uncertain factors cause the living costs (such as the cost of electricity bills) of residents to fluctuate. In some cases, the government intends to reduce the negative impacts of rising costs on residential living standards by adopting corresponding measures such as subsidy policies. In this regard, the DPI can be referenced when formulating measures. Therefore, the indicator of DPI should be considered when evaluating energy systems. The desired direction for this indicator is POSITIVE.
 6. **Electricity generation cost:** The trajectories of electricity generation costs indicate that the trends seen over the last few years, whereby solar PV, wind, and battery storage technologies have reduced their costs at a faster pace than most other generation technologies, will continue [37]. These substantial and ongoing cost reductions have also begun to impact the cost and adoption of other generation technologies. Consequently, the prediction of electricity generation costs is included in Australian electricity modelling studies as a scenario input. Therefore, the indicator of electricity generation costs should be considered when evaluating energy systems. The desired direction for this indicator is NEGATIVE.
 7. **Installed capacity of Rooftop PV:** The installed PV capacity in Australia increased 10-fold from 2009 to 2011, quadrupled in 2016, and reached its highest growth period in 2017–18 [38]. The largest share among the installations in 2018 was from grid-connected distributed systems, which are rooftop systems in the residential, commercial, and industrial sectors. Therefore, growing rooftop PV system installations should be considered to comply with increasing power demand and the realization of the RE target. The desired direction for this indicator is POSITIVE.
 8. **Total energy consumption per capita:** Energy plays a crucial role in our daily lives and economic activities. Therefore, the energy consumption per capita of a country is regarded as an important indicator of economic development. In the long-run, economic growth has a positive effect on energy consumption, while technology development or innovation can reduce it. Generally, electricity consumption grows gradually during industrialization and diminishes when industrialization is complete or nearing completion [39]. Considering the Australian industrialization level and the future investment in energy infrastructure, the desired direction for this indicator is a slight NEGATIVE.
 9. **Transmission and distribution loss per capita:** The increasing penetration of RE generation in the power system will directly affect the transmission and distribution loss. This indicator reflects the technical progress and operational efficiency of future power systems. Targeting higher energy efficiency, the investment in energy infrastructure should aim to reduce the total loss when integrating renewable power generation. The desired direction for this indicator is NEGATIVE.
 10. **Annual growth rate (AGR) of real GDP per capita:** The link between energy consumption and economic growth is not always unidirectional. The dynamic characteristics of each are complex and context dependent. Stable and increasing access to electricity and other energy sources may provide an initial increase in GDP which may in turn lead to higher energy consumption (rebound effect). This is often the case in a high-income country like Australia. Note that progress in economic development outcomes can be sophisticated: a number of parameters may be changing at the same time. The desired direction for this indicator is POSITIVE.
 11. **Life-cycle CO₂ emissions from electricity:** The decarbonisation of the electricity infrastructure has been extensively studied for years. The life-cycle assessment (LCA) of CO₂ varies between different technologies, and system designs, system operating assumptions, and technological advancement can all contribute to its evaluation [40].

- The shift to high-quality RE infrastructure should take life-cycle-based CO₂ emissions into account as the electricity sector exhibits significant emission reduction potential among other sectors, especially at the utility level. The desired direction for this indicator is NEGATIVE.
12. **Energy intensity measured in terms of GDP:** Energy intensity is a widely used indicator to reflect the energy productivity of an economy. It is often measured as the total primary energy demand per unit of GDP. It has been extensively explored at national and industry levels. Drivers of influence and consumption-based studies have been prevalent in academia. The desired direction for this indicator is NEGATIVE.
 13. **Total quantity of RE:** Existing federal emissions reduction policies require the reduction of Australia's emissions by 26–28% from 2005–2030, with a commensurate degree of decarbonisation in the electricity sector [41]. To reduce emissions of greenhouse gases, the Australian Government designed the RE target scheme. In line with this scheme and increasing power demand, a growing target of RE should be considered. The desired direction for this indicator is POSITIVE.
 14. **Total installed utility-scale battery storage capacity:** In line with the increasing uptake of PV systems and the decreasing power system inertia, the capacity of BESSs in all regions presents a rising trend, especially at utility-scale. Similarly to PV systems, the increasing trend of BESSs is inevitable considering the financial incentives, declining installation and system costs, changes in retail prices, assumptions on the transition to a time-of-use tariff structure, and steady population growth. The desired direction for this indicator is POSITIVE.
 15. **Life-cycle water consumption for electricity:** The power sector is vulnerable to water constraints and water scarcity. Academic research regarding the energy-water nexus (water embodied in energy commodities) has been carried out, and its trade implications have been extensively studied at national and regional levels [42–44]. Therefore, the shift to high-quality RE infrastructure should consider a life-cycle-based water consumption indicator at the infrastructure level to improve water use efficiency and visualize water risk. The desired direction for this indicator is NEGATIVE.
 16. **Fossil fuel consumption in the total electricity generation:** The production of raw material and its extraction processes often result in high environmental degradation. However, the material requirements and associated environmental impact on the low-carbon electricity system are rarely modelled in conventional scenario-based energy infrastructure models. Therefore, the shift to high-quality sustainability infrastructure should take into account a life-cycle-based material consumption indicator at the infrastructure level to improve resource efficiency and sustainable material consumption practices [45]. The desired direction for this indicator is NEGATIVE.
 17. **Land use of PV and wind generation:** Compared to fossil fuel-based generation, RE generation requires much more land use. This is usually accompanied by problems that may limit the expansion of renewable generation, including land costs, planning restrictions, environmental impact assessments, visual impact, and other influential factors related to stakeholders. Therefore, the development of RE generation should consider changes in land use. Meanwhile, the desired direction of this indicator is determined by both the technical progress of RE generation and increasing load demand. When the rate of development rate RE installed capacity is faster than the rate of progress of PV and wind generation efficiency, more land usage is expected to occur. The indicator here refers to the total occupation of land resources by PV and wind generation. Considering the rapid growth of installed RE generation capacity in recent years, the desired direction for this indicator is POSITIVE.
 18. **Level of electrification of transportation:** A report on Australian energy in 2019 indicates that transport accounts for approximately 28% of Australian energy consumption in recent years [46]. The heavy reliance on fossil fuels results in the transportation sector contributing approximately 18% of Australia's annual greenhouse gas emissions [47]. However, the higher level of transport electrification means higher reliance on the electricity supply, which makes the electricity cost an influential factor to electrification. The desired direction for this indicator is POSITIVE.
 19. **Total PM2.5 emissions:** This indicator is of great relevance to the public health sector as the production of fossil fuel electricity such as coal and gas can trigger cardiovascular-disease-related mortality and reduce life expectancy. Meanwhile, the closure of Australia's major fossil fuel electricity generators is on the move. Most major producers have set out their policy to prepare for the gradual decarbonisation of their electricity generation portfolio. Decommissioned facilities are to be transformed into energy recovery facilities, or the investments may be redirected to RE. The desired direction for this indicator is NEGATIVE.
 20. **Subsidies to fuel and energy:** Fuel and energy taxes and subsidies are essential parts of the Australian government's expenditure administered by the Australian taxation office. They cover fuel tax credits, product stewardship waste schemes, as well as other expenses related to improving energy efficiency, resource-related initiatives, and RE-related programs. In energy systems, changes to such subsidies can offer direct and indirect support to energy production and consumption activities. Therefore, this indicator should be considered when evaluating the development trends of future energy systems. The desired direction for this indicator is POSITIVE.
 21. **Electricity sector specific employment:** The installation, construction, and operation of new renewable generation facilities helps to create new job opportunities. Although a deep understanding and assessment of the net job creation of a low-carbon electricity system may vary, the shift to high-quality sustainable infrastructure

- should consider an electricity sector specific employment indicator. The desired direction for this indicator is POSITIVE.
22. **Utility-scale PV installed capacity:** The Australian Large-scale Renewable Energy Target scheme will expire soon, without an explicit substitution policy promised. Moreover, the aging energy infrastructure, especially the transmission network, is holding back the development of utility-scale PV systems due to capacity limitations, voltage issues, lack of inertia, etc. This has resulted in decreasing demand for utility-scale PV generation, especially after 2018. According to a recent report, the investment in utility-scale PV systems fell to US\$1.2 billion in 2019 from US\$3 billion in 2018 [48]. This changing trend has impacted on the management costs of energy transmission and generation systems. Therefore, the capacity of newly installed utility-scale PV systems should be taken into consideration when evaluating Australia's future energy system. The desired direction for this indicator is NEGATIVE.
 23. **Average number of outages per customer:** In Australia, blackout events are typically triggered by various factors including faulty equipment, human error, weather, falling trees, and other incidents. Such unexpected power outage events not only directly reflect the problem of power system reliability, but also affect people's daily activities. Therefore, an indicator related to the average number of outages per customer should be considered when evaluating energy systems from a social sustainable development perspective. In this regard, the unplanned system average interruption frequency index (SAIFI), a commonly used indicator to analyse power system reliability, is adopted as the indicator. The desired direction for this indicator is NEGATIVE.
 24. **Ancillary service payment:** The Australian energy market operator (AEMO) is in charge of the procurement of ancillary services in the NEM, including network support and control ancillary services (NSCAS), system restart ancillary services (SRAS), and eight types of frequency control ancillary services (FCAS), from registered service providers. With the increasing penetration level of RE, the demand for auxiliary services in power systems will increase. From an economic sustainability perspective, the development of energy systems should consider an indicator related to ancillary service payment. Under the current level of ancillary service technology development, the desired direction for this indicator is POSITIVE.
 25. **Fluctuation of wholesale electricity prices:** In a competitive market environment, the fluctuation of wholesale electricity prices reflects changes in the supply and demand, to a large extent. Although the costs and benefits of price fluctuations are borne by electricity suppliers (retailers), the results will be reflected in the price for consumers, from a long-term perspective. In the short-term, a severe fluctuation of wholesale electricity prices indicates insufficient reliability of the power sys-

tem, which requires setting a higher reliability standard. However, the implementation of higher reliability standards in turn brings higher costs to consumers, according to the Australian energy market commission (AEMC) [49]. Hence, the volatility of wholesale electricity prices directly reflects both the short-term and long-term stability of electricity market economics, which is eventually linked to general economic sustainability. Therefore, the fluctuation of wholesale electricity prices should be regarded as an economic indicator when evaluating the Australian energy system. The desired direction for this indicator is NEGATIVE.

The assessment of energy system intelligentisation is an essential but challenging problem in the sustainability assessment of energy infrastructure. Artificial intelligence (AI) is regarded as one of the most revolutionary technologies in terms of the decarbonisation of energy systems, energy consumption reduction, the increased stability of power grids, the increasing penetration of renewables, and the intelligent use of resources. In [50], the current and potential impact of digital technologies within cyber-physical systems (CPS) on the decarbonisation of energy systems was assessed. The assessment shows that the digitalization of energy systems using CPS completely alters the marginal abatement cost curve (MACC) and creates novel pathways for the transition to a low-carbon energy system. The benefits of adding intelligence to small-scale RE systems were studied in [51], and the evaluation of the management algorithms was carried out using simulation data. In particular, the evaluation of system intelligence of the intelligent building systems was presented in [52]. Key intelligent indicators were identified and analytical decision models were developed to assess the system intelligence of the intelligent building systems. Meanwhile, the availability of historical data is also crucial when establishing a framework for the quantitative sustainability assessment of energy infrastructure. Therefore, only indicators with sufficient data were selected for the key index framework of this article.

4 | CASE STUDY AND DISCUSSIONS

The new vision for Greater Sydney's future involves a major shift in strategic planning focusing on the regional development of Western Sydney. The planned investment for building a liveable and productive Western Sydney, particularly the Western Sydney Aerotropolis project, is recognized as a game-changer and transformational point in creating a polycentric city metropolis [53]. The New South Wales (NSW) government has also released a series of reports, including the 'Western Sydney City Deal' [54], 'Towards Our Greater Sydney 2056' [55] and 'Towards a resilient Sydney-Socioeconomic profile' [56], to guide the sustainable development of Western Sydney. In this case study, Western Sydney is taken as an example to test the proposed key index framework of sustainability assessment.

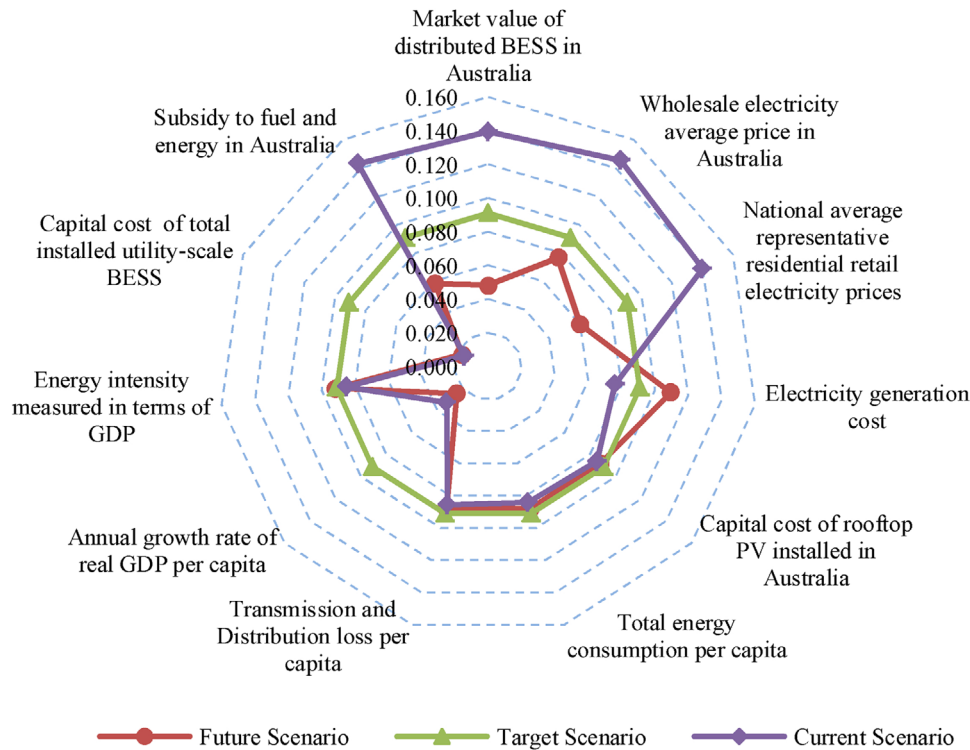


FIGURE 5 Radar diagram of indicators in the economy domain

4.1 | Data specifications in the case study

In this case study, three scenarios regarding future energy systems were considered, including the current scenario, the future scenario for the year 2030, and the target scenario which is specified in the long-term development plan of Western Sydney. Meanwhile, related datasets with respect to the energy infrastructure in NSW were collected through a comprehensive survey. However, due to the non-availability of local historical data, some national-scale energy data were used instead. Table 3 presents the selection of indicators in the case study. All these indicators were finally selected after the correlation analysis between indicators and the growth of RE, and only indicators with a correlation result $\rho \geq 0.4$ were finally selected in the key index framework. Furthermore, three of the indicators in Table 3, namely No. 9, No. 11, and No. 22, were re-used as No. 16, No. 30, and No. 29. This was because each of these indicators could be simultaneously assigned to multiple domains, as long as they could contribute to a proper assessment of these domains.

When setting indicator values under a target scenario, the targets set by governmental development policies were directly referred to, if available. If not available, the simulation of indicator future values was carried out under low, medium, and high development trends. Subsequently, the indicator simulation values under the medium trend were adopted as target values. Furthermore, in the simulation of indicator future values, the AGR and CI methods were adopted depending on the availability of the indicator’s historical data. Details of these two methods are

presented in Section 2.2. When there was sufficient data for implementing either the AGR or the CI methods, one of these two methods was randomly selected. The method adopted for each indicator simulation is presented in Table 4. Furthermore, the indicator values under current, future, and target scenarios, as well as the calculation results of the indicator scores are shown in Table 4. In addition, as for the weighting factors, each indicator i that belongs to the same domain was assigned the same weighting factor w_i derived from Equation (10).

4.2 | Visualization of assessment results and analysis

Scores of each indicator in the economy, environment and society domains are presented in Figures 5–7, respectively. In general, it can be seen that these indicators respond to the development of energy systems in different ways.

To be specific, in the economy domain, there needs to be a decrease in the fuel and energy subsidies, market value of distributed BESSs, wholesale electricity prices, and residential retail electricity prices in the future in order to achieve the sustainable development target. However, attention should be paid to the generation costs. Although its current value is within the target level, there will be an increase during future development, and it could escalate beyond the target values without interventions. Regarding the capital cost of utility-scale BESS and the AGR of real GDP per capita, efforts should be made to

TABLE 3 Selection of indicators in the case study

No.	Domain	Indicator title	Unit	Correlation	Selection
1	Economy	Market value of distributed BESS in Australia	Million \$	0.802	Select
2	Economy	Wholesale electricity average price in Australia	\$/MWh	0.916	Select
3	Economy	National average representative residential retail electricity prices	c/kWh	0.850	Select
4	Economy	Electricity generation cost	\$/kW	0.957	Select
5	Economy	Capital cost of rooftop PV installed in Australia	Million \$	0.787	Select
6	Economy	Total energy consumption per capita	GJ	0.892	Select
7	Economy	Transmission and Distribution loss per capita	GJ	0.704	Select
8	Economy	Annual growth rate of real GDP per capita	%	0.903	Select
9	Economy	Energy intensity measured in terms of GDP	(koe/\$)	0.894	Select
10	Economy	Capital cost of total installed utility-scale BESS in Australia	Million \$	0.626	Select
11	Economy	Subsidy to fuel and energy in Australia	Million \$	0.886	Select
12	Economy	Capital cost of installed utility-scale PV in Australia	Million \$	0.121	Delete
13	Economy	Ancillary service payment	Million \$	0.050	Delete
14	Economy	Fluctuation of wholesale electricity prices	Standard deviation	0.334	Delete
15	Environment	Capacity of total installed distributed BESS in Australia	GWh	0.911	Select
16	Environment	Capacity of total installed distributed BESS in Australia	MW	0.905	Select
17	Environment	Capacity of total installed rooftop PV in Australia	GW	0.974	Select
18	Environment	Life-cycle CO ₂ emissions from electricity generation	10 ³ kt CO ₂ eq.	0.912	Select
19	Environment	Energy intensity measured in terms of GDP	(koe/\$)	0.894	Select
20	Environment	Total quantity of RE in Australia	GWh	0.916	Select
21	Environment	Capacity of total installed utility-scale BESS in Australia	GW	0.931	Select
22	Environment	Life-cycle water consumption for electricity	Million gallons /year	0.200	Delete
23	Environment	Fossil fuel consumption in the total electricity generation (measured by electricity-fuel ratio: Tons of fuel / TWh of electricity)	Ratio	0.917	Select
24	Environment	Land use of PV and Wind generation in NSW	Hectares	0.739	Select
25	Environment	Level of electrification of transportation (measured by quantity of electricity consumption in transportation)	GWh	0.931	Select
26	Environment	Total PM _{2.5} emission	μg/m ³	0.990	Select
27	Environment	Capacity of total installed utility-scale PV in Australia	GW	0.959	Select
28	Society	Capacity of demand-side participation in NSW	MW	0.886	Select
29	Society	Penetration level of distributed generation in NSW	%	0.936	Select
30	Society	Total amount of disposable personal income in Australia	Million \$	0.958	Select
31	Society	Ratio of rooftop PV systems installed in Australia (measured by % in total generation capacity MW)	%	0.957	Select
32	Society	Market share of electric vehicles (measured by % in total amount)	%	0.815	Select
33	Society	Total PM _{2.5} emission	μg/m ³	0.990	Select
34	Society	Subsidy to fuel and energy in Australia	Million \$	0.886	Select
35	Society	Electricity sector specific employment in NSW	Person years	0.298	Delete
36	Society	Penetration level of utility-scale PV in Australia (measured by % in total generation quantity GWh)	%	0.945	Select
37	Society	Average number of outages per customer (measured by unplanned system average interruption frequency index in Australia)	Frequency	0.950	Select

achieve a future increase in these areas, in order to meet the final sustainable development target. Furthermore, as for the other indicators including energy intensity measured in terms of GDP, the transmission and distribution loss per capita, the total energy consumption per capita, and the capital cost of rooftop

PV installed in Australia, their future values will need to be well controlled around current levels during the period of sustainable development.

As for the environmental indicators, sustainable development requires a further increase in the capacity of installed

TABLE 4 Scores of finally selected indicator in the case study

Original No.	Desired direction	Weight factor	Current scenario	Target value in 2030			Method of indicator simulation	Indicator score		
				Method of setting target	Target scenario	Simulation of future scenario		Current scenario	Future scenario	Target scenario
1	Negative	0.091	1.229×10^2	Simulation	188.291	355.334	AGR	0.139	0.048	0.091
2	Negative	0.091	84.590	Simulation	135.430	160.820	AGR	0.146	0.077	0.091
3	Negative	0.091	28.500	Simulation	43.874	66.451	AGR	0.140	0.060	0.091
4	Negative	0.091	2.622×10^3	Simulation	2.192×10^3	1.864×10^3	CI	0.076	0.110	0.091
5	Negative	0.091	7.301×10^3	Simulation	6.880×10^3	7.125×10^3	CI	0.086	0.088	0.091
6	Negative	0.091	30.510	Simulation	28.154	29.148	CI	0.084	0.088	0.091
7	Negative	0.091	1.858	Simulation g	1.753	1.819	CI	0.086	0.087	0.091
8	Positive	0.091	0.948	Refer to [57]	2.640	0.721	CI	0.033	0.025	0.091
9	Negative	0.091	0.110	Simulation	0.104	0.103	CI	0.085	0.091	0.091
10	Negative	0.091	1.165×10^3	Refer to [58]	200	1,054	AGR	0.016	0.017	0.091
11	Negative	0.091	8.171×10^3	Simulation	1.285×10^4	2.004×10^4	AGR	0.143	0.058	0.091
15	Positive	0.083	0.286	Refer to [59]	5.580	4.175	CI	0.004	0.062	0.083
16	Positive	0.083	40	Simulation	114.125	136.433	AGR	0.029	0.100	0.083
17	Positive	0.083	6.83	Refer to [60]	19.70	17.15	CI	0.029	0.073	0.083
18	Negative	0.083	174.707	Refer to [61]	155	138.311	CI	0.074	0.094	0.083
19	Negative	0.083	0.110	Simulation	0.104	0.103	CI	0.078	0.084	0.083
20	Positive	0.083	4.003×10^4	Simulation	4.210×10^4	4.214×10^4	AGR	0.079	0.084	0.083
21	Positive	0.083	0.375	Simulation	1.182	1.585	AGR	0.027	0.112	0.083
23	Negative	0.083	0.870	Simulation	0.825	0.346	CI	0.079	0.195	0.083
24	Negative	0.083	72.729×10^3	Simulation	1.114×10^5	1.948×10^5	CI	0.128	0.048	0.083
25	Positive	0.083	2.210×10^5	Simulation	2.831×10^5	3.027×10^5	AGR	0.065	0.089	0.083
26	Negative	0.083	7.434	Simulation	7.006	5.709	CI	0.079	0.102	0.083
27	Positive	0.083	3.100	Refer to [62]	15	11.870	CI	0.017	0.066	0.083
28	Positive	0.111	164	Simulation	382.057	263.051	AGR	0.048	0.076	0.111
29	Positive	0.111	13.500	Refer to [63]	44	52.596	AGR	0.034	0.133	0.111
30	Positive	0.111	3.203×10^5	Simulation	4.293×10^5	4.492×10^5	CI	0.083	0.116	0.111
31	Positive	0.111	16.010	Simulation	37.559	39.290	CI	0.047	0.116	0.111
32	Positive	0.111	0.481	Simulation	20.990	22.579	CI	0.003	0.120	0.111
33	Negative	0.111	7.434	Simulation	7.006	5.709	CI	0.105	0.136	0.111
34	Positive	0.111	8.171×10^3	Simulation g	1.285×10^4	2.004×10^4	AGR	0.071	0.173	0.111
36	Positive	0.111	4.816	Refer to [64]	30	23.301	CI	0.018	0.086	0.111
37	Negative	0.111	0.982	Simulation	0.404	0.459	CI	0.045	0.097	0.111

Note. The “Original No.” means the numbering of indicators appeared in Table 3; AGR represents the annual growth rate method and CI denotes the confidence interval methods as is presented in Section 2.2.

utility-scale PV, the capacity of installed distributed BESS (in terms of either GWh or MW), the capacity of installed rooftop PV, the capacity of utility-scale BESS, and the level of electrification of transportation. These indicators all need to be further improved through new investment or incentive policies. On the other hand, the land use of PV and wind generation should be managed to improve usage efficiency. In addition, the current indicator values of total PM2.5 emissions, the life-cycle of CO₂ emission from generation, the energy intensity measured in terms of GDP, the total quantity of RE, are all at an accept-

able level compared with the target scenario. Notably, although the current fossil fuel consumption in the total generation is within the target range, measures should be prepared to prevent its potential increase.

When assessing the sustainability of a smart city from the perspective of society, all social indicators, except the total PM2.5 emission, tend to increase with the increasing penetration of RE in the energy system. In particular, the energy system operator needs to guarantee system security and stability during future development since the average number of outages per customer

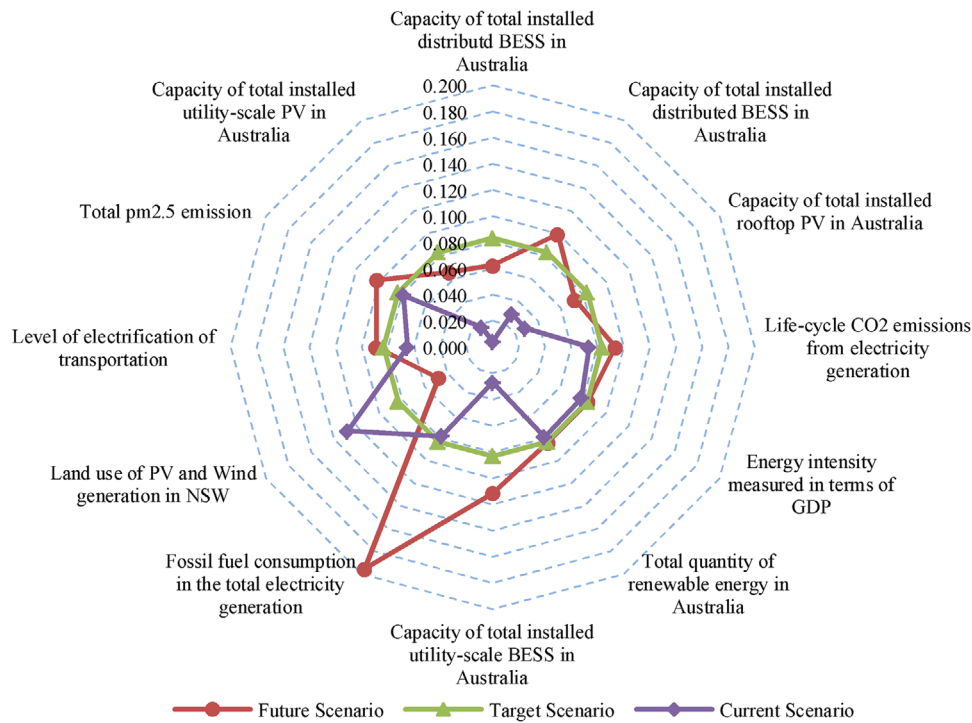


FIGURE 6 Radar diagram of indicators in the environment domain

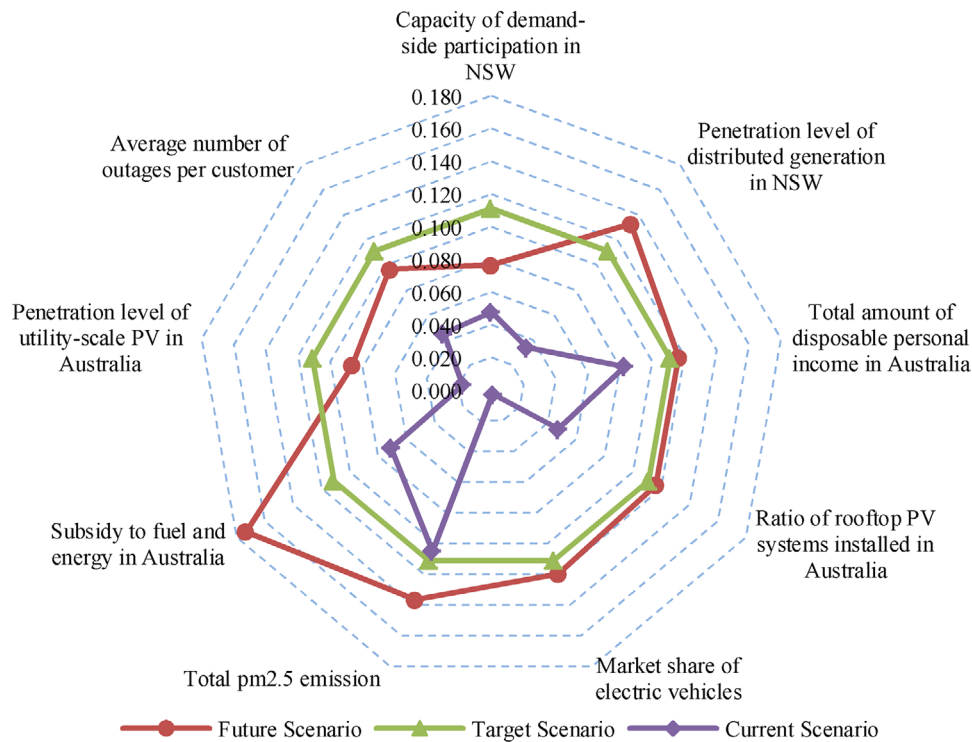


FIGURE 7 Radar diagram of indicators in the society domain

will negatively impact people’s daily activities. Moreover, from the perspective of the economy, sustainable development means a decrease in the subsidy to fuel and energy but in the social domain, an increase of subsidy to fuel and energy is beneficial to

sustainability. Therefore, it is essential to ensure that each indicator is assigned to a specific domain before being applied in the sustainability assessment. As for the PM2.5 emission, similar results have been observed in both the environment and

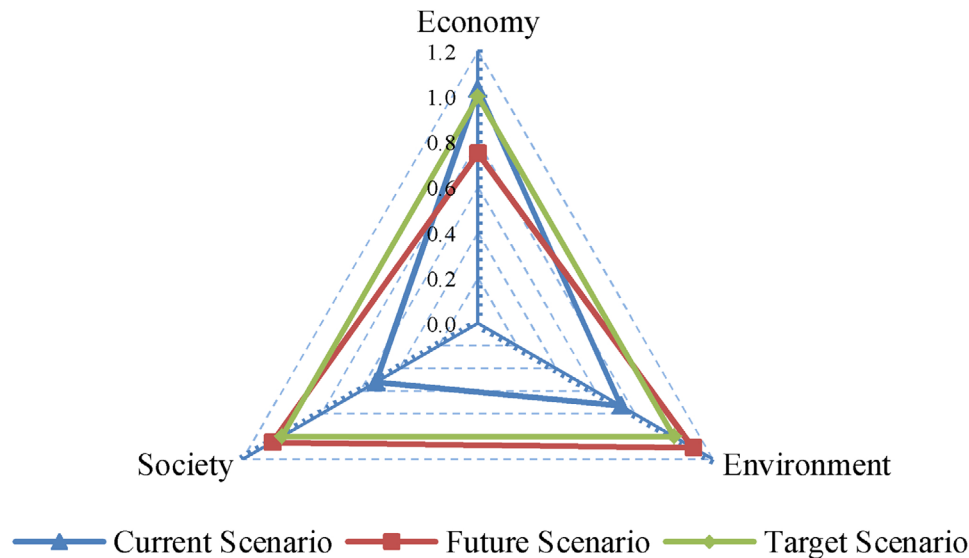


FIGURE 8 Triangle diagram of the case study results

society domains. This means that its current indicator value is at an acceptable level compared with the target scenario, but it could escalate beyond the target without interventions in future scenarios.

The overall performance of indicators in these three domains is shown in Figure 8. From the perspective of the economy, the current scenario already has a similar score to the target scenario. In the social and environmental domains, however, the scores in the current scenario are far smaller than those in the target scenario. On the other hand, in the future scenario, the social and environmental domains will have reached target levels or more, while a smaller economic score is envisaged in the future. In other words, under the current development trends in the case study, although sustainable development can be achieved from a social and environmental perspective, the impacts on economic sustainability should have increasing importance attached to them by related authorities. To realize balanced sustainable development, the authorities can filter out indicators with unexpected results, especially under the unsatisfied domain, and then make improvements through corresponding measures, such as project approval, the issue of policies, budget allocation, and planning adjustments. Additionally, the authorities can regularly forecast the indicators based on new historical data to evaluate the effectiveness of their measures or decisions.

5 | CONCLUSIONS

Due to concerns regarding energy security and the ongoing environmental crisis, the sustainable development of human civilization has attracted significant attention from both industry and academia. In this context, this study proposed a key index framework for quantitatively assessing the sustainability of energy infrastructure in a smart city. In order to guide

users on the selection of indicators, a three-tier story chart for indicator selection was developed. Then, a detailed analysis of indicator selection was presented. The established framework incorporates extensive economic, environmental, and social indicators into its design. Finally, a case study of the Western Sydney area was conducted to demonstrate the feasibility and efficiency of the proposed methodologies. It was found that several indicators could be assigned to multiple domains, such as the indicator of fuel and energy subsidies, and it was essential to ensure that each indicator was assigned to the desired domain(s) before conducting the sustainability assessment. If not, it could cause disputes when interpreting the results from different perspectives. Meanwhile, sustainability assessment should cover all of the economy, environment, and society domains to achieve balanced development. In terms of future work, since data availability is essential for accurate sustainability assessment, machine learning based methods will be studied to overcome this problem. Furthermore, the correlation between indicators will be investigated, and other advanced indicator forecasting techniques will be considered to further improve the proposed methodology.

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