**ORIGINAL RESEARCH**

# Green and renewable resources: an assessment of sustainable energy solution for Far North Queensland, Australia

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## Abstract

Remote communities, which do not have a connection to the national grid in Far North Queensland (FNQ), depend on dirty and costly diesel generators to meet their energy demands. The cost of power generation is considerable in those areas, because the diesel fuel must be carried by truck or ship and a fuel reserve must be held on-site in case of expected demand or weather closure. Moreover, Australia has an energy security issue in relation to liquid fuels. Australia is reliant on imported fuel such as diesel to fill the shortage, as domestic production and supply are unable to fulfil domestic demand. As a result, by deploying hybrid integrated renewable energy systems in remote areas, isolated communities may lower their power prices, enjoy a more secure and dependable source of electricity and minimise their carbon footprint by eliminating or reducing the usage of diesel. In this study, an extensive literature review has been conducted focussing on renewable resources for Australia and Far North Queensland, different hybrid energy systems including energy storage, and finally highlights the alternative clean and renewable energy options for Far North Queensland (FNQ) remote communities. In addition, this study has performed an assessment of renewable energy available from solar and wind resources considering climatic, geographical and economic aspects for FNQ. The literature review and the assessment show that solar and wind resources including hydrogen storage have significant potential for energy solution of FNQ. The assessment results indicate that selected regions of FNQ have suitable land area of 142,294.86 km$^2$ (55.94% of total selected areas) for solar and 144,563.80 km$^2$ (56.83% of total selected areas) for wind. The total calculated potential power can be 14,448 GW from solar PV and 1040.97 GW from wind energy. This study provides a significant pathway for parties interested in investing in renewable energy in FNQ. Moreover, knowing a land's suitability will increase confidence and hence speed up the renewable energy investment.

**Keywords** Renewable energy · Hydrogen · Solar farm · Wind farm · Electrical power potential · GIS

## Introduction

The rapid socio-economic uplift, including population growth, technology upgradation, trade, increased production and consumption, has made the relations between Earth and human beings deeper than ever. Consequently, fossil fuel reserves are depleting so quickly to meet the energy demands, which are the globe's current issue. The gathering of greenhouse gases in the atmosphere, causing global warming and the urgent requirement of renewable and eco-friendly energy resources has been a great concern. Apart from that, energy demands are growing every day with the globe's population which may grow up to roughly 9.9 billion by 2050 [1]. At the same time, developing countries will have to enhance energy expenditure intensely because of their spreading economy [2].

To be sustainable, a society needs high and constant amounts of energy with limited environmental impact. There are many remote areas in the FNQ, and they have to rely on diesel power generation for fulfilling their basic energy requirements [3]. However, diesel is one kind of fossil fuel which has limited stock. In addition, the diesel power generation is costly [4] and harmful to the ecosystem because of its greenhouse gas emissions [5]. To

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keep the globe environmentally sustainable, so that the civilisation can continue for a longer time, the resources of the earth should not be changed from the equilibrium levels which help to sustain the ecosystem for thousands of years. Simultaneously, the world has to limit carbon emissions. The incoming energy resources, the solar and wind, should be trapped, not the energy system innate in the globe. Solar energy can be exploited in several ways: utilising solar cells to convert solar to electricity [6], and wind energy to generate electricity [7]. Wind energy is, in reality, a secondary effect consequencing from solar energy [7, 8].

FNQ has an abundance of solar and wind resources that have bright potential towards the fruitful sustainable pathways. However, the intermittency or unsteady nature makes solar and wind less secure, incapable of providing energy at all times [9]. There is one that sounds to be consistent with promoting energy security and cleanliness, that is hydrogen. Hydrogen is an energy carrier, convenient to transform from different energy sources, and possesses the highest amount of energy by weight compared to any common fuels [10, 11]. Hydrogen leverages the utilisation of solar and wind, as they can be used to generate hydrogen, which can then be utilised at any time for fulfilling energy needs [12]. Furthermore, if hydrogen is generated through water splitting and used in fuel cell for power production, it will produce only water as a by-product, with no hazardous emissions [11]. This is called green hydrogen. Therefore, solar and wind including green hydrogen, with their promising clean features, could be the best option for the future energy system of FNQ and Australia in general.

The motive of this study is to find out the solution for reducing the impact of diesel generation so that the remote communities can sustainably lead their life in a sustainable way. In this study, an extensive literature review has been conducted. The review focuses on renewable resources in an Australian context, emerging hybrid renewable energy systems, hydrogen storing options, renewable generation in Australia and the renewable energy potential in FNQ. In addition, a potential assessment of solar and wind resources has been conducted in terms of climatic, geographical and economic to see the suitability for the growth of solar and wind projects. The main objectives of this study to find a sustainable solution for FNQ's energy system can be summarized as follows:

1. Survey on renewable resources and its' potentiality, renewable generation in Australia;
2. Explore suitable resources for FNQ's energy system;
3. Investigate suitable lands to install solar and wind power stations, using the multi-criteria Geographical Information System (GIS) modelling technique.

To date, this is the first elaborate study where FNQ has been explored to identify potential resources as well as to investigate the suitability of places for solar and wind analysis using GIS. Finally, as this study covers the potential of renewable resources, especially the two most mature technologies, namely solar and wind including hydrogen storage, and location suitability for the installation of solar and wind farm, hence it can be expected that it will give valuable insights for hybrid versions of solar and wind including hydrogen energy applications. The present article is structured into six sections, including introduction (Sect. 1), global weather pattern (Sect. 2), global energy demand and consumption (Sect. 3), literature review that presents overview on renewable resources of global and Australian perspective, electricity energy value chain and different hybrid energy systems, potential of hydrogen energy storage, renewable generation in Australia and renewable resource potential in FNQ (Sect. 4), assessment of solar and wind resources presenting climatological, geographical and economic potential including discussion about the importance of solar and wind energy development for FNQ's energy system (Sect. 5). The last section presents the main conclusions and future perspectives.

## Weather pattern

The weather pattern has been changing; for example, the global surface temperature increment, narrowing the cryosphere extensively including weight loss from ice sheets and glaciers, depletion in snow cover and Arctic Sea ice extent and thickness [13]. Global warming is responsible for extreme events, such as more extended periods of heat, heavy rainstorms and oceans acidification because of absorbing carbon dioxide [14]. All weather-related problems are happening because of the greenhouse gas (GHG) emissions in the atmosphere. Global surface temperature increment may cause more drought and damage of agricultural land. In addition, extremely hot weather may push people from their motherlands and compel them to move to other areas, eventually driving them to compete for depleting resources in their areas of arrival. Coastal regions can be invaded by multiple natural hazards such as tornado, extreme sea levels and flooding. The ocean temperature increment will also pose marine lives at possible food insecurity risk. Ultimately, a change in the weather pattern will result in changing ecosystem structure and functioning, which may cause losing the globe's unique biodiversity [13, 15]. Figure 1 highlights some indicators of global warming that were examined over the past decades [16, 17]. The globe's climate system comprises the land surface, atmosphere, oceans and ice. As seen in Fig. 1, white arrows indicate rising trends and black arrows indicate declining trends.
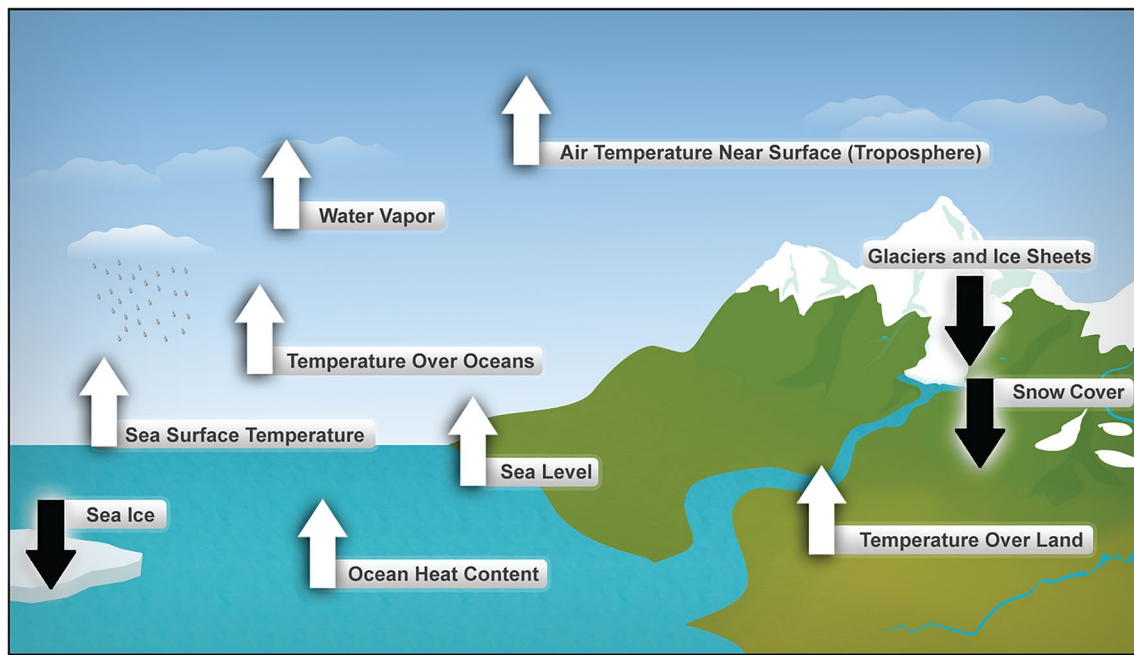
**Fig. 1** Ten indicators of the global warming [16, 17]

Global warming is augmented at an average rate of 0.08 °C per decade since 1980 and over twice that rate since 1981. In 2020, the global surface temperature augmented at an average of 0.98 °C, which is the second highest record in the last 141 years [18]. If the present trend continues, the global temperature may reach to 1.5 °C between 2030 and 2052 [18, 19]. The Intergovernmental Panel on Climate Change (IPCC) [20] reported that the global mean sea level was augmented from 1.4 mm per annum (1901–1990) to 3.6 mm per annum (2006–2015); the 0–700 m and 700–2000 m layers of the ocean were warmed at rates of $6.28 \pm 0.48$ ZJ and $3.86 \pm 2.09$ ZJ, respectively, from 1993 to 2017. In addition, the continual ocean acidification because of carbon uptake (the ocean surface water pH level has been falling at a range of 0.017–0.027 pH units per decade since the 1980s) including oxygen vanished with a loss of 0.5–3.3% between 1970 and 2010 from the ocean surface to 1000 m [20]. Numerous peer-reviewed literature has already been reported about the weather extremes around the world, such as droughts in South Africa [21], extreme heatwaves in Sweden [22], excessive 6-day rainfall in Bangladesh [23] and hurricanes in the Caribbean [24]. These extreme weather events are due to the global surface temperature increment which are likely to be the results of the accumulation of GHG (carbon di-oxide, nitrous oxide, methane, halocarbons) in the atmosphere [25].

The global atmospheric concentration of carbon di-oxide has raised from a preindustrial (1750) level of 280 ppm to 417.64 ppm (March 2021), nitrous oxide from 270 to 333.6 ppb (Nov 2020), methane from 715 to 1892.3 ppb (Dec 2020) [26, 27]. As seen in Fig. 2, maximum greenhouse gas (GHG) emissions come from fossil fuel sources that are used in different economic sectors [28]. Among the GHG, carbon di-oxide is the most abundant in the atmosphere, hence the main contributor to global warming. Figure 3 depicts the trend of the increment of the global annual mean temperature anomaly with the concentration of carbon dioxide in the atmosphere [29, 30].

Australia's climate is changing in response to global warming, with an average temperature increment of $1.44 \pm 0.24$ °C since the Australian observations commenced in 1910 [31]. The most warming has been happening since 1950, and since then, Australia is getting warmer and warmer every decade. For instance, Australia suffered 43 exceedingly hot days in 2019, more than three times as many as in any year before 2000. High monthly maximum temperatures, around 2% during 1960–1989 and over 4% during 1990–2004, have recently been over 12% during 2005–2019. [31]. This number is more significant than a sixfold increment over the 60 years. Climate change is observed across the whole Australia. All areas of Queensland are warming since 1910, with an average annual temperature increment of 1.5 °C. Rainfall has increased in most parts of Queensland during the summer or humid season [32]. The number of days including threatening weather conditions for bushfires has augmented in all regions across the state. Sea levels are predicted to rise by nearly 26 cm along the coast of

**Fig. 2** Global GHG emissions by economic sectors in 2016 [28]



**Fig. 3** Global annual mean temperature anomaly and carbon dioxide concentration [29, 30]
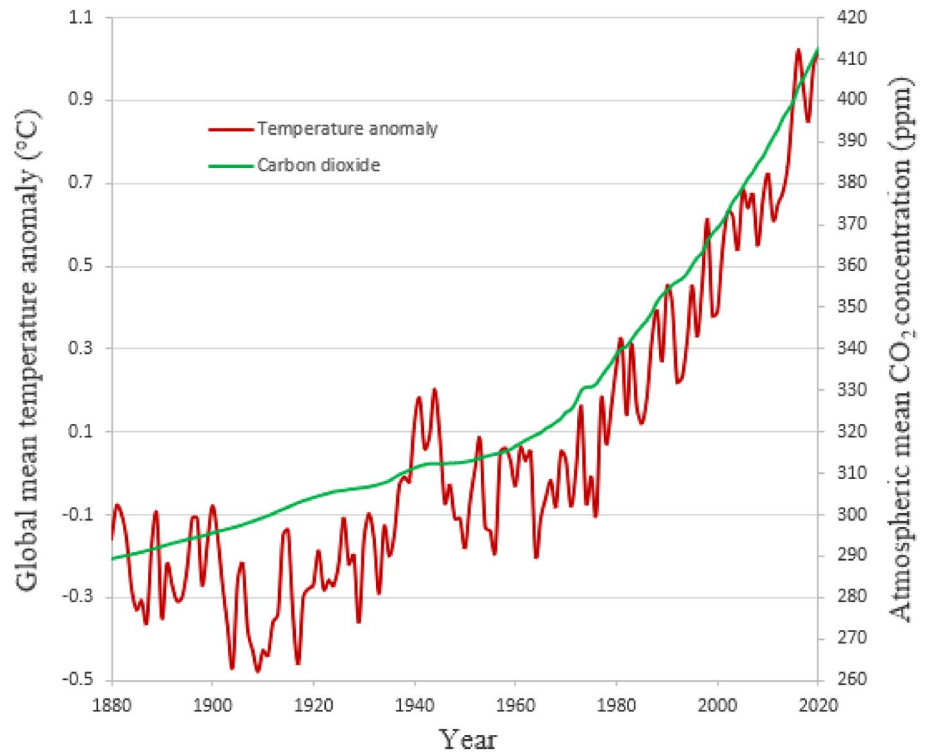
Queensland. Queensland may face more extreme rain events in the near future [32].

The FNQ region is specifically in danger because of the impact of climate change. Alteration in temperature or rainfall may impact significantly on the tourism, agriculture, dairy, cane and fisheries sectors [33]. Local community will also be affected, as climate change may augment heat-related health problems and potentially increase catastrophic occurrences, such as cyclones and floods, with endangering lives and infrastructure. Healthy reef and rainforest environs are the core for the tourism industry. These ecosystems are particularly at risk because of the adverse effect of climate change. Raising temperatures may constantly cause coral bleaching in the Great Barrier Reef, and this impact will become more severe if the temperature continues to increase [33]. The deterioration of the reef will be a destroy of the distinguished innate value for FNQ, which will ultimately adversely affect the tourism industry. Furthermore, sea water acidification has been occurring due to the continuous absorption of carbon dioxide. Continual acidification can affect coral formation [33, 34], which would further exacerbate the vulnerability of the Great Barrier Reef.

The globe is warming continuously, and if the GHG emissions are not controlled immediately and strong development of fossil fuel plants continues, then the globe's surface temperature may rise by 4 °C, or more, within 2100 [35], including terrible impacts on the globe's ecology and substantial demolition of the world's major coastal parts [36]. A maximum of 2 °C of global mean surface temperature deviation from pre-industrial level is the widely accepted climate policy target, but the temperatures above 2 °C will cause the ecosystems to be highly vulnerable [37]. In addition, without taking any action against GHG emissions, climate change might cost as high as 5–20% of the global gross domestic product (GDP) per year [36]. Specially, developing countries like Africa may face more difficult situations with the GDP losses as high as 26.6% per year [38]. Instead, taking action might cost 1% of the global GDP per year [36]. So, it is from an economic point of view that worldwide investment is inevitable now for the drawdown of GHG emissions and fossil fuel utilisation by alternative approaches to energy production that could potentially arrest the current climate trend.

## Energy demand and consumption

Energy is the crucial and fundamental element for the global civilisation. There is a close and firm relation among the energy supply, national and international security, human basic needs and economic growth and the ecological pollution. Hence, energy is a complicated issue now, while the global energy demand continues to rise. Energy, as a production input or as a direct component of human well-being, is the key component of economic development. Its uninterrupted supply with increased global demand continuously poses a significant challenge to society. The global energy demand may rise by 30% within 2035, driven by emerging economies such as China, Brazil, Russia and India [39]. But the demands are fulfilled mainly by fossil fuels. The ongoing fossil fuel utilisation is posing a threat to the planet by emitting GHG [39]. Figure 4 depicts the energy consumption of different fuels in 2020, where it is seen that fossil fuels are dominating the energy regime. However, the pandemic Covid-19 causes global energy demand to decline by 4.5% in 2020, which is the biggest fall since World War II [39].

The downfall in demand in 2020 did not influence all fuels evenly. Oil was the hardest hit, with restrictions on transport resulting in demand dropping by a remarkable 9.3%—the biggest drop in history [39]. However, the oil demand bounced back by 5.7 mb/d in 2021 [40], which is faster than any other fuel. Coal demand declines globally by 4% in 2020, but the coal utilisation for power generation in advanced economies dropped down by 15%, more than a half of coal's global decline.

Low power demand increased renewable power generation and low gas prices squeezed coal utilisation in power generation. However, coal demand rebounded strongly in 2021, although with vast, diverse geography [39]. In contrast, natural gas showed far greater resiliency in 2020, with demand dropping only by 2.3%. Due to low prices and rapid growth in economies across Asia and the Middle East, in 2021, global gas consumption rebounded by 4.6%, the most substantial rebound among all fossil fuels and double the decline that occurred in 2020 [41]. In 2020, the low gas prices caused a gas generation to obtain a share in the US power market as well as sustain in the European Union (EU) [39].

Global power consumption experienced a smallest drop, 0.9% in 2020. Despite the drop in overall power
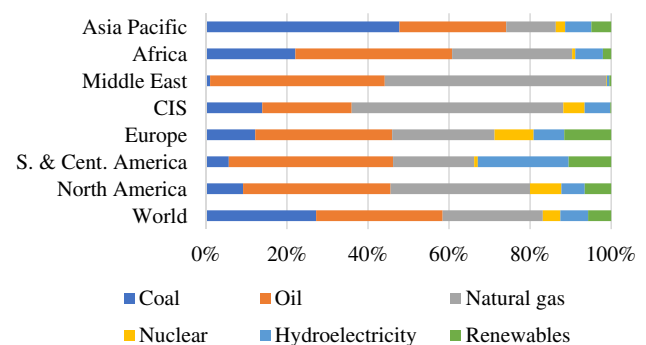
**Fig. 4** Global energy consumption by fuel in 2020 [39], note: CIS-Commonwealth of Independent States

consumption, renewable generation (wind, solar, geothermal energy, bioenergy, and excluding hydroelectricity) boomed to 358 TWh, the highest ever increase. This achievement was gained by the strong growth in both wind (173 TWh) and solar (148 TWh) generation. The continued deployment of renewables including power demand falls hurt coal utilisation in 2020, losing competitiveness especially in the USA and EU. However, 'more than doubling' in the wind and solar power generation over the last 5 years has not made even a tiny dent in total coal production. Essentially coal production level in 2020 was unchanged from that's level in 2015, since last year's decline just counterbalanced the previous few years' increments [39]. Although the continued deployment of renewable, it cannot keep up with the rising demand. The world will need more than a just strong growth in renewable energy to banish coal from the power sector. It is still long to put coal out of the power sector.

Global power demand rebounded strongly in 2021, boosted by more than 6%. 2021 have experienced the biggest ever annual rise, over 1500 TWh [42]. Coal served more than half of the additional demand in 2021, raising in absolute terms faster than renewable energy for the first time since 2013. Global power demand is expected to grow by around 3 to 4% in 2022, 2.6% in 2023 and above 2% in 2024 [42], as energy efficiency measures start showing effects. However, fossil fuel-based power generation may grow by 0.2% annually from 2022 to 2024, but still is expected to serve 58% of total power generation in 2024, with coal-based power generation to serve 34% in 2024 [42]. Hence, the world will be still affected by fossil fuels including GHG increment in the upcoming years.

The increment of GHG should be minimised as soon as possible to avoid severe ecological damage [43]. Therefore, time is crucial now and an urgent energy transition is pivotal. The German Advisory Council on Global Climate Change [44] has drawn attention to the energy transition that it could benefit a double dividend: 'Not only will it prevent a fatal degradation of the global environment, but it could also create the basis for a new economic dynamism, with positive effects on employment, prosperity and equity'. To narrate it more pointedly, there are many indications that the renewable energy transition is an opportunity to reshape the prevalent energy regime to sustain the natural life support system, which will rescue the global economy. Decarbonisation is at the centre of the path of transition towards sustainability to battle against climate change, which can be succeeded by massively expanding renewable energies while giving access to modern energy for the billions of people living in energy poverty.

The remote communities of FNQ are leading their lives in a very unsustainable way. Currently, for their basic energy needs, they are heavily reliant on the diesel generator [3] which is associated with limited resource diesel including higher, unstable fuel prices [4] and greenhouse gas emissions, damaging the biota including trees, vegetation and marine lives. In addition, the diesel fuel must be shipped by truck or ship to the remote areas. Fuel reservation on-site is necessary in case of higher power demand than expected or the area being cut-off by any weather event. Therefore, this worse situation underscores the requirement for developing a new energy system with the minimal environmental impacts. By utilising hybrid renewable energy systems at isolated locales, remote communities can minimise their power costs and can have a more secure and consistent power supply with diminished carbon emissions because of no or less diesel.

FNQ region, with an area of 380,748.3 square kilometres [45], is one of the most attractive tourist destinations in Australia. The region has a number of World Heritage Sites, including the Great Barrier Reef, the Wet Tropics of Queensland and Riversleigh, Australia's largest fossil mammal site [33, 46]. But climate change, mainly due to the use of fossil fuels, is exacerbating extreme weather events that threaten FNQ's unique features and tourism industry [33].

## Literature review

### Renewable resources

Energy resources are categorised into three types: (1) fossil fuels, (2) renewable and (3) nuclear. Renewable resources are non-depletable sources that emit very low or no greenhouse gases. A superabundance of renewable resources exists, namely: wind, solar, hydro, biomass, geothermal, tidal and ocean—all these resources are vastly available and easily exploitable in Australia's geographical and political context. Solar and wind power generation have been proved to be the most logical and easily harvested option of all renewable resources available. Solar is vast, and the globe receives solar irradiation on an average 1.6 MWh/m$^2$, which is potent to fulfil the annual world energy requirements [47].

The red sea regions including Saudi Arabia and Egypt are receiving the highest amount of solar irradiation, while Australia and the USA receive above average solar irradiation [49]. Figure 5 reports that the largest solar radiation greatly blesses the north-west and central regions of Australia. Australia is receiving on an average 35 megajoules per square metre per day or 58 million petajoules per annual of solar irradiation (around 10,000 times Australia's annual energy consumption), the world's highest solar radiation [50]. There is also notable solar potential in areas with access to the electricity grid. The annual solar irradiation fallen onto the areas within 25 km of existing transmission lines is around 500 times larger than the yearly Australian energy consumption [50].
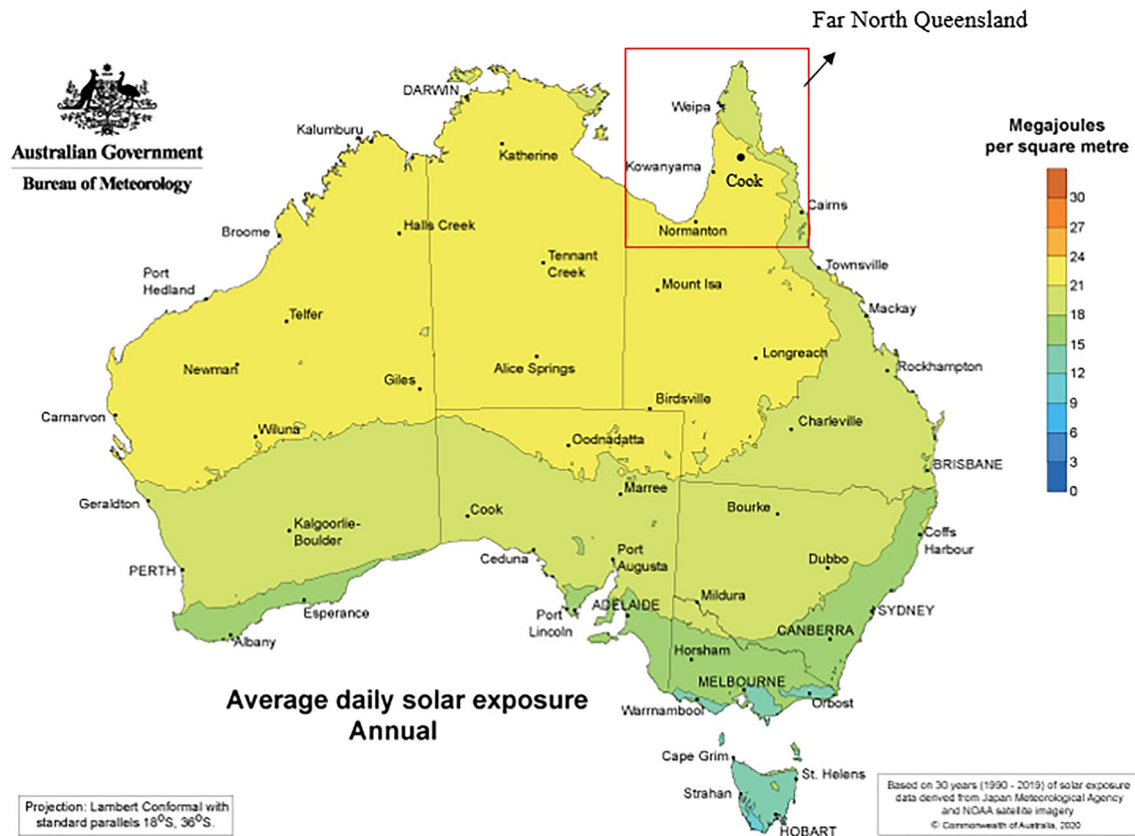
**Fig. 5** Australian average daily solar exposure [48]

With the prospective and rapid growth in solar energy exploitation, wind energy is the fastest-growing source in Australia. Australia is one of the best continents in the world for having high wind resources that primarily are located in south-western, southern and south-eastern regions and extending hundreds of kilometres inland and including highland areas in south-eastern regions [51, 52]. Wind has already been proven as one of the least-cost power options. Small-scale wind turbines are sufficient to serve the remote community power needs, as well as large-scale wind farms could be a feasible option instead of fossil fuels [53].

Hydropower has been utilised for 135 years to convert the energy of water to electrical energy. Hydropower was developed in Australia in the nineteenth century within the areas of high rainfall and elevation such as Tasmania and New South Wales. Hydropower, including installed capacity of 8790 MW, is the 2nd largest renewable resource in Australia, and Australia is the world's fourth-largest producer of hydropower [54]. However, Australia's hydropower development trend is relatively slow due to a notable lack of viable on-river locations, variable annual rainfall, high temperature, very high evaporation rates [55].

Ocean renewable energy from ocean waves, tidal and ocean currents, has significant potency in Australia. The first ocean power patent was reported in Australia in 1909; after that the twenty-first century has seen significant government investment and private venture capital-funded developments [56]. Australia's wave energy resource is the most significant source on earth [57]. Australia's best wave energy resources are located along the southern and western coastlines. The total wave energy on entire Australia is on average, approximately 3.125 petajoules (PJ) [57], and it could meet a maximum of 11% of Australia's total energy demand by 2050 [58]. Australia also has good opportunity to exploit mechanical energy from tides, current and waves, and ocean thermal energy from the sun's heat. The Australian government has funded projects aiming to make this inborn energy as a major contributor to the country's energy mix by 2050. The Australian Wave Energy Atlas (as shown in Fig. 6) is one of the first outputs of this agenda which forms the Australian Renewable Energy Mapping Infrastructure [59]. However, ocean energy technologies are relatively new and still need to be proven in pilot and demonstration plants. Also, these technologies are significantly more expensive than other, more mature forms of variable renewable energy.

Australia has notable hot rock geothermal resources, capable of producing superheated water or steam suitable for base load electricity generation. There are also
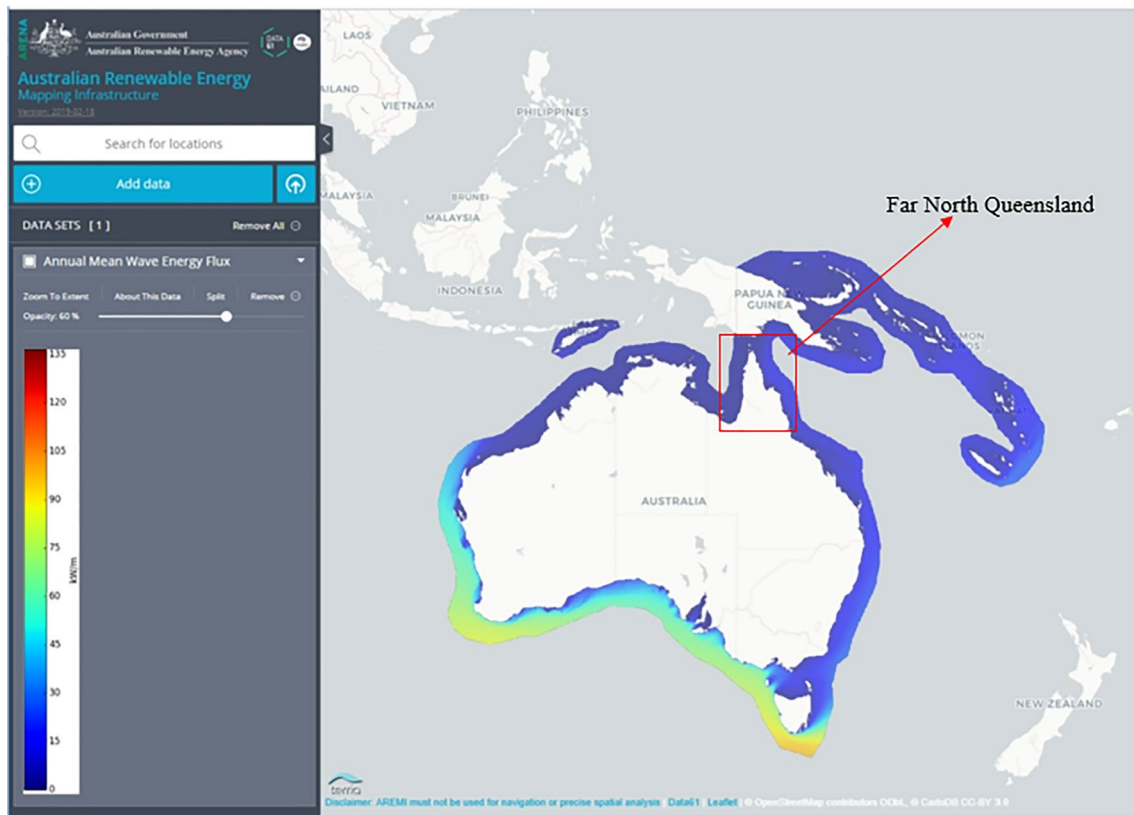
**Fig. 6** The Australian wave energy atlas, displaying the annual mean wave energy flux (in kW/m) and the Australian Renewable Energy Mapping Infrastructure (AREMI) [59]

potential lower temperature geothermal resources in a number of sedimentary basins for power generation or direct-use applications.

## The global electricity energy value chain and emerging hybrid renewable energy systems

The electricity energy value chain comprises all functions required to generate, distribute and consume power. Figure 7 presents the electricity energy value chain, which can be segmented into five major parts: fuel procurement, electricity generation, transmission, distribution and end user [60]. Due to the irresistible challenges of increasing power demand, depletion of fossil fuels, the emergency for decarbonisation and power accessibility, the energy communities [4] are reshaping the energy value chain:

(1) A paradigm shift-decentralised or distributed generation network has appeared as an alternative to highly centralised architecture; decentralisation is observed and reflected through the envelopment of micro-grids which comprise distributed renewable resources, battery storage, load and controlling systems;

(2) The deployment of hybrid integrated renewable energy system is continuously increasing for maximising the usage of locally distributed and dispersed renewable resources;

(3) The scope of hybrid energy system for grid connection or Power-to-X applications.

A hybrid energy system constitutes more than one energy source: either renewable or non-renewable sources so that one source being unavailable can be substituted by another available sources to ensure sustainable power supply. This is a worthy option to meet the power demand from locally available energy sources for regions where grid extension is expensive or power transmission from centralised utility is difficult. Utilising only locally available renewable resources to provide power is a sustainable option for human beings. A hybrid system constituting only renewable resources has benefits where fuel cost inclines, fuel transport is expensive, and globe's ecological system is worsening. But due to the unpredictable, seasonal and time-dependent natures, renewable resources are not entirely reliable options. In this regard, including an energy storage system is one kind of approach for hybrid systems [61].

**Fig. 7** The electricity energy value chain [60]
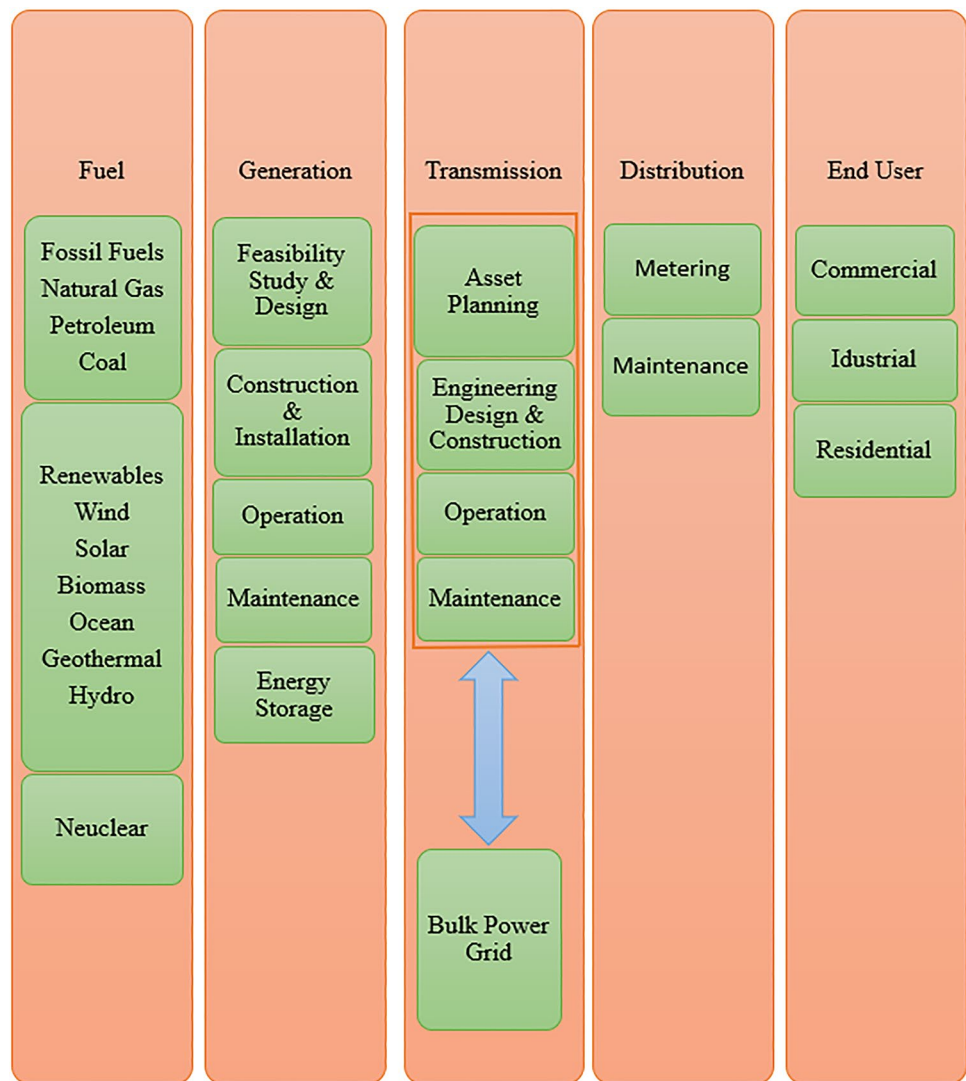


Solar PV is dominating in off-grid installation among all renewable systems [62, 63]. Lower maintenance and more straightforward implementation make PV a common and more suitable option in many off-grid applications [64]. Along with the PV, wind power has already shown itself as a very low-cost and promising option. Albeit solar PV and wind can supplement each other to handle intermittent nature and can enhance overall reliability [65], an energy-storing stuff, such as batteries, ultra-capacitors and fuel cells, is normally an essential option to manage renewable intermittency, enhance energy efficiency and assure secure and good-quality power supply [66, 67]. Diesel generators are sometimes used as back-ups to reduce power loss probability in off-grid hybrid systems [68, 69].

Widespread implementation of solar and wind energy generation system accredits to the global reachability of these resources and naturally complements characteristic of solar and wind resources. Research regarding complementing effects of different renewable resources has been conducted in recent studies [70, 71]. In addition, integrating hydro [72, 73], geothermal [74], biomass [68, 75, 76] and tidal [77] energy resources alongside solar and wind resources, instead of diesel generator, which is related to higher fuel and maintenance cost, have been suggested in recent research work. Recent research indicates that HRES can be implemented not only in remote areas or in off-grid conditions such as sites away from the national grid or at satellite earth stations [78], but also in a grid-connected conditions or Power-to-X applications such as direct charging of electric vehicles (EV) [79], renewable hydrogen generation [80], chemical production [81], desalination [82, 83] and multi-generation [84].

# Hydrogen: a new opportunity towards the decarbonisation

The ecological damage due to global warming and excessive energy needs has put unprecedented pressure on the world to seek clean alternative energy options. The most important and immediate factors to be considered in seeking alternatives are their prospective curtailment of high levels of GHG and other emissions hazardous to the ecosystem. Clean renewable energy sources have become a global concern in this context. Recently, along with the available renewable resources, hydrogen is regarded as the major option in this sustainable journey of seeking. Hydrogen has far reached significance for energy security, emission mitigation and green economic development.

Theoretically, hydrogen could be imagined as an infinite supplement, if renewable energy is implemented to generate hydrogen through water electrolysis and then discharge the chemical energy through the reaction of hydrogen gas and oxygen gas to water. It is the greatest attraction of hydrogen to be present in water, which covers about 71% of globe's surface [85]. If hydrogen can be generated from water economically, it can be a future energy provider as well as can concurrently diminish emissions in various sectors such as the power sector, transportation and industry [86]. Moreover, compared to solar, wind and geothermal resources, which have limitation of their own volatile and intermittent nature, hydrogen with no toxic emissions and greater energy content (higher energy density: between 120 and 142 MJkg$^{-1}$, around 3 times greater than fossil fuels) can be an excellent option for future energy systems [10, 11, 87].

The world was experienced energy transition a long time ago. Wood was the main source of energy since several 1000 years ago. The usage of coal did energy transition to fossil fuel, while the industrial revolution happened in the eighteenth century [88]. Then the transition from coal to petroleum occurred by 1930. The invention of the internal combustion engine accelerated oil utilisation, which peaked in 2000 to meet the world's energy needs. Since 1970 natural gas utilisation enhanced gradually and is hoped to reach a climax by 2050 [88], when the hydrogen energy carrier may take the global lead in fulfilling energy needs. However, shifting from one fuel to another has not wiped out the previous ones; rather, their exploitation has been superimposed with much higher amounts. Wood, coal, oil and natural gas are providing energy concomitantly and recently in complement to that modern windmills and solar PV are supplying energy also.

A noticeable fuel transition has happened. Wood contains more complex chemical structure and lower specific energy (20.6 MJkg$^{-1}$) than coal (23.9 MJkg$^{-1}$) [89]. Similarly, coal has more complex chemical structure and lower specific energy than oil (45.5 MJkg$^{-1}$), which continues this

trend with natural gas (52.2 MJkg$^{-1}$) [89]. Additionally, this shifting seems to be the continual decarbonisation of fuels. Because, the carbon quantity declined from wood to coal, to oil, to natural gas. It is also surprising that the hydrogen quantity enhances continuously from wood, to coal, to oil, to natural gas, ultimately to arrive at the perennial, carbon-free hydrogen.

Figure 8 depicts the trend towards the decarbonisation of the global energy supply, from one based on mainly carbon to one that is based on hydrogen. This trend reflects the hydrogenation of the global energy supply, which means the global movement towards the hydrogen energy carrier. It is noteworthy that clean hydrogen or ammonia has no relation with any carbon emission.

The transition to the hydrogen energy era has already been started worldwide with marked participation of renewable resources. Australia is not out of this hydrogen race. Clean hydrogen production at low cost is one of the priority stretch goals under the Australian government's 2020 Low Emissions Technology Statement [94]. FNQ needs clean, versatile, flexible, storable and safe fuels to support the energy needs with mitigating carbon emissions. Hydrogen possesses all of these features. When hydrogen is generated using renewable energy through water electrolysis, and fuelled into fuel cells to generate power, it produces only water, with no carbon emissions [11]. In addition, renewable energy's inherent intermittency can be complemented well by the production and storage of hydrogen. Thus, hydrogen can be a mode of reserving renewable energies for utilising at a later time when it is required, resulting in a yearly, renewable and sustainable circular cycle. Storing hydrogen can act as a buffer for enhancing the resiliency of the energy system of the remote parts of FNQ, thereby stabilising the regional electrical network. Eventually, utilising renewable resources to produce hydrogen is of immense potential for
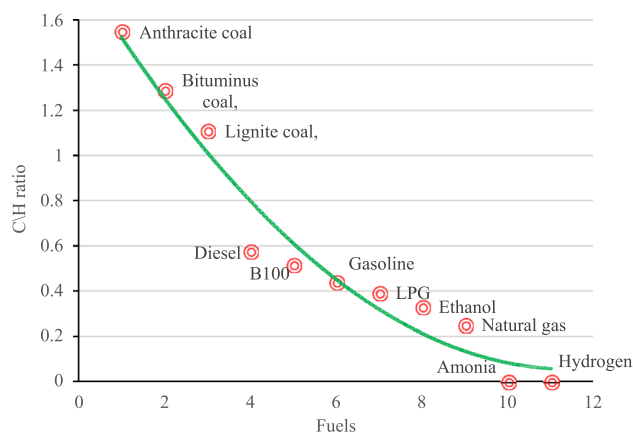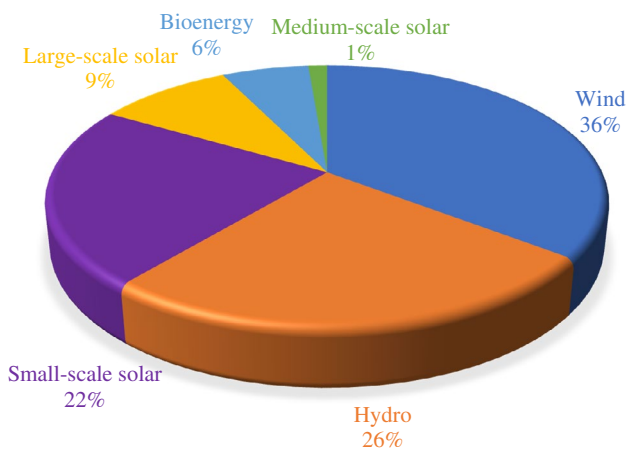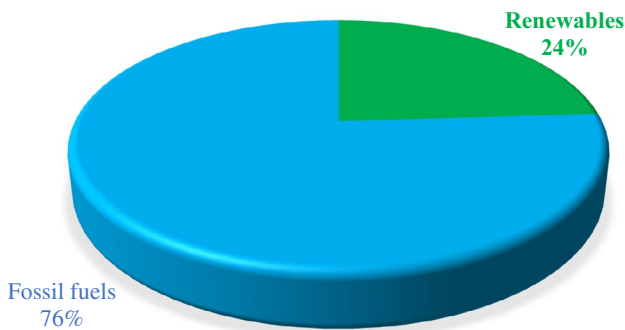


**Fig. 8** Carbon/hydrogen ratio of common fuels [89–93]

**Fig. 9** Renewable energy generation in Australia by different technology [52]



**Fig. 10** Total electricity generation in Australia in 2019 [52]

the remote parts of FNQ, with their own local specificities in terms of raw materials and energy sources.

## Renewable energy generation in Australia

Australia has a rich, diverse renewable resource ranging from solar, wind, bioenergy, geothermal to ocean energy. The exploitation of solar and wind energy has been

increasing since 2010 and continues rapidly. Before 2019, hydro energy was the most significant generator of renewable electricity among all renewable resources. In 2018, hydro energy provided 35.2% of generation (17,002 GWh) of total renewables. 2019 is the best year for wind, which has taken over the mantle as Australian's clean energy leader, accounting for 35.4% renewable power generation (as shown in Fig. 9). Australia has demonstrated record in 2019, that renewable power generation accounts 24% of total electricity generation (as shown in Fig. 10), an increase of 2.7% on 2018 [52].

The completion of the Large-scale Renewable Energy Target (LRET) was the largest achievement for 2019, which is more than a year ahead of the 2020 deadline. Australia has attained the LRET in September 2019 following the 148 MW Cattle.

Hill Wind Farm [52]. This remarkable milestone has transformed renewable energy from one of the most expensive energy generations to the cheapest. The contribution of different renewable sources to national power generation is presented in Table 1.

Australia has six states: New South Wales, South Australia, Tasmania, Victoria, Queensland and Western Australia with two mainland the Australian Capital Territory and the Northern Territory. Figure 11 illustrates the contribution of renewable generation to supply consumers in each state in 2019.

Tasmania is in the leading position for using renewable energy with a penetration level of 95.6%. Due to the shutting down of Northern coal-fired power stations [95], renewables provide 52.1% of South Australia's electricity, special thanks to hydro and wind energy. Still, Queensland has the largest fossil fuel power generation and is very low in renewable generation, while Tasmania has the biggest total renewable generation [95].

## Renewable energy potential in FNQ

Queensland is the fastest-growing and most energy-intensive state in Australia. The GHG emissions in Queensland are

**Table 1** Power generation by renewable resources in Australia [52]

| Resources | Generation (GWh) | Percentage of renewable generation (%) | Percentage of total generation (%) | Equivalent number of households powered over course of the year |
|---|---|---|---|---|
| Wind | 19,487 | 35.4 | 8.5 | 4,240,013 |
| Hydro | 14,166 | 25.7 | 6.2 | 3,082,150 |
| Small-scale solar | 12,269 | 22.3 | 5.3 | 2,669,440 |
| Large-scale solar | 5141 | 9.3 | 2.2 | 1,118,596 |
| Bioenergy | 3314 | 6.0 | 1.4 | 7,21,005 |
| Medium-scale solar | 716 | 1.3 | 0.3 | 155,867 |
| Total | 55,093 | 100.0 | 24.0 | 11,987,070 |
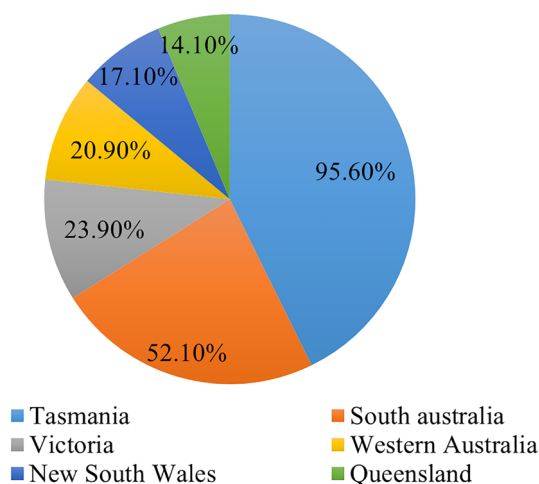
**Fig. 11** Renewable power penetration in Australia by state in 2019 [52]

approximately 43 tonnes per capita, greater than that in any other state [96]. With the strong growth in power demand, Queensland is facing the challenge of mitigating the rise in GHG emissions. Because of the vast geographical area and highly decentralised population, Queensland faces challenges in ensuring cost-effective and reliable power supply to remote and sparsely populated regions [96]. The remote parts of Queensland still meet their power demand by mainly the diesel power generation, which needs fuel with fluctuating prices and maintenance. Renewable energy could be an option in addressing all these challenges, and FNQ has a vital role to play in this regard.

The FNQ has a powerful combination of solar, wind, hydro and bioenergy resources. The region has dozens of sites suitable for off-river pumped hydro to store and release clean power on demand. Solar and wind farms in FNQ can generate 20–50% more electricity per unit than most other countries. Even wind generators in the region often can be operated at times when southern wind farms are idle [97]. However, hydropower plants have geographical constraints including harmful dams for marine species. Biomass resources are not entirely green as they emit some GHG. They are also associated with transportation and processing costs. On the other hand, solar and wind have less impact than hydro and biomass.

In this study, the main concern is about the remote areas of FNQ such as Cook shire, Doomadgee, Burke, Pormpuraaw, Northern Peninsula, Umagico, Mapoon, Torres shire, etc. There are some renewable solutions including community-scale solar PV in few remote parts such as Doomadgee, Mapoon, Pormpuraaw, the Northern Peninsula Area, but diesel power generation is still dominating in the remote areas of FNQ [3]. These areas are full of abundant solar and wind resources. Solar irradiation and wind speed

are considered high in these regions which is the proof of potency for the development of renewable energy systems, that can replace the present diesel power generation system [3].

## Assessment of solar and wind resources

### Climatological potential

Solar irradiation in Central and North Queensland including FNQ can be considered as one of the highest amounts in the globe, only the Northern and the Southern African desert and the Southwestern United States receive a comparable amount [98]. The combined sunny climate and latitude of FNQ exhibit potentiality for solar electricity generation. Any area receiving solar irradiation of greater than 4 kWh/$m^2$/day can be geographically potential for harnessing solar energy [99].

FNQ receives average daily solar irradiation, that is greater than 5.5 KWh per square metre per day [98], more than enough with annual average daily sunshine hours of 7 to 8 (as shown in Fig. 12). Figure 13 presents monthly mean daily global horizontal irradiation for some selected remote areas of FNQ, which varies between 4 and 7.5 kWh/$m^2$/day [101], which is the proof of FNQ's promising potential to harness solar energy. It is also seen that Mornington Island has peaked in November recording 7.3 kWh/$m^2$/day, followed by Cook at 7 kWh/$m^2$/day, Lockhart at 6.8 kWh/$m^2$/day and Burke at 5.9 kWh/$m^2$/day. On the other hand, Aurukun, Carpentaria and Kowanyama have recorded a maximum of 7.2 kWh/$m^2$/day in October, followed by Doomadgee and Pormpuraaw at 7.1 kWh/$m^2$/day, Napranum and Torres shire at 7.0 kWh/$m^2$/day, Mapoon and Northern Peninsula area at 6.7 kWh/$m^2$/day.

Similarly, wind resource in FNQ is another potential option for power generation, with annual average wind velocity at 80 m above ground level ranging from 5.6 to 10 m/s (as shown in Fig. 14). Previous studies considered the minimum mean daily wind velocity 4 m/s [103] and 5 m/s [104] for installing wind farm. In addition, the mean operational cut in velocity for the Vestas V117-3.45, horizontal axis wind turbine, which is used in Mount Emerald wind farm in Arriga (FNQ), is 3 m/s [105, 106] and this indicates that FNQ is the best suited to wind energy.

### Geographical potential

Suitable place identification to install solar and wind farm is a complicated task. Moreover, issues such as meteorological needs, ecological concerns and financial gains, also need to be considered for plant installation and operation [107, 108]. Area with the abundant resources such as solar irradiation
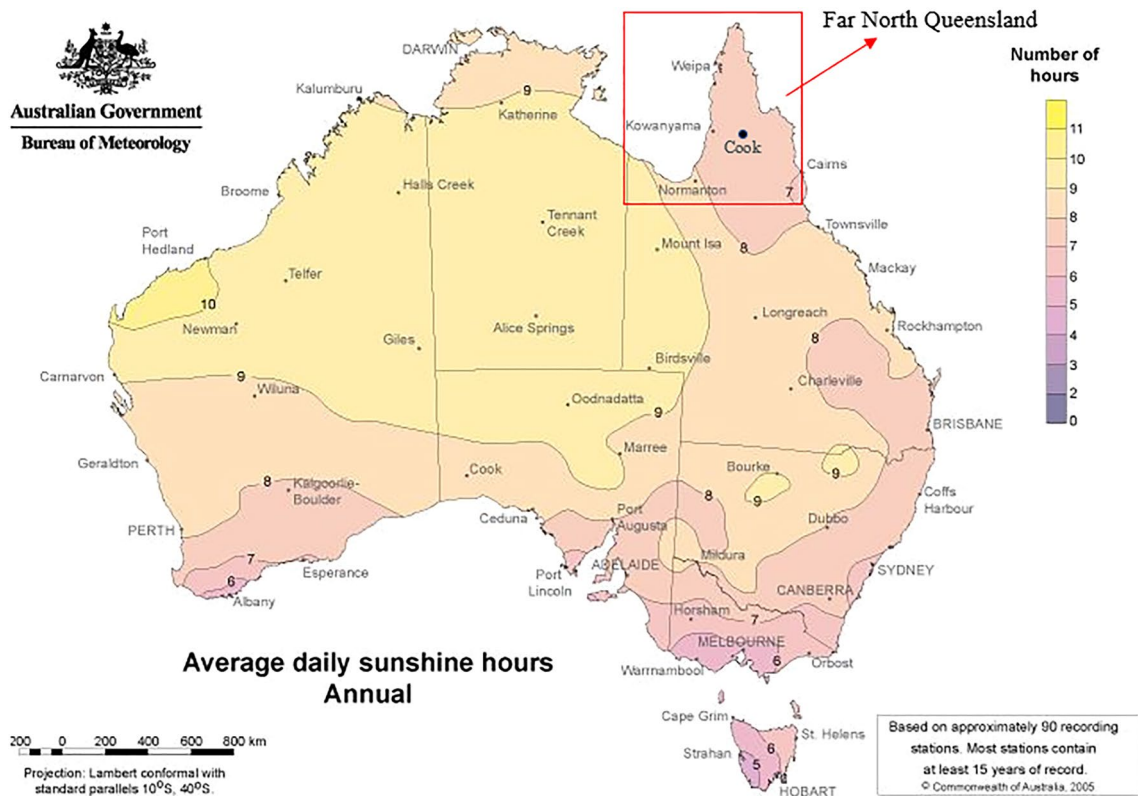
**Fig. 12** Annual average daily sunshine hours in Australia including FNQ [100]
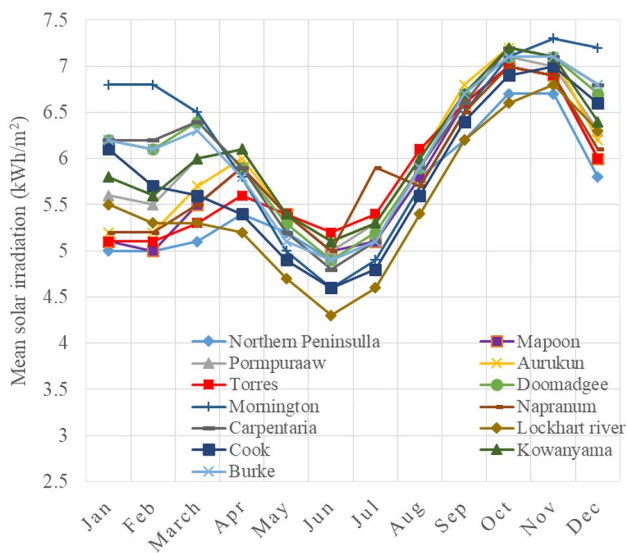


**Fig. 13** Monthly mean daily solar irradiation in selected regions of FNQ [101]

and wind velocity may not be the only feasible thing. Some other factors that can also be crucial for the evaluation of suitable places, such as social, economic and environmental constraints [109, 110]. Recently, Geographical Information

System (GIS) has appeared as the most convenient and proficient tool, and is being employed by many countries for assessing renewable energy potentiality [111, 112]. GIS tool can digitise, convert, analyse and visualise spatial data [113]. GIS can handle a range of environmental, financial, social and regional aspects for planning renewable energy development. It has inbuilt abilities to investigate the territories, generate and sort data, capture the geographical information, manage commands and visualise the output [113]. GIS data give an appropriate path to ascertain a suitable place considering location-specific circumstances (social and environmental limitations and resource availability) [114–116]. GIS includes various built-in tools; the present study principally utilises data management, conversion and spatial analysis tools. In this study, to perform GIS-based analysis, several remote areas from FNQ have been selected, namely Cook, Carpentaria, Burke, Doomadgee, Mornington Island, Kowanyama, Pormpuraaw, Aurukun, Injinoo, Torres, New Mapoon, Umagico, Mapoon and Lokhart river.

All topographical data are extracted from different digital databases that are given in Table 2. Unsuited locations have been omitted utilising different tools of ArcGIS. Firstly, data management toolbox is used to make projection of all GIS data layers (vector and raster) on a similar coordinate system, project tool for vector data and project raster tool for
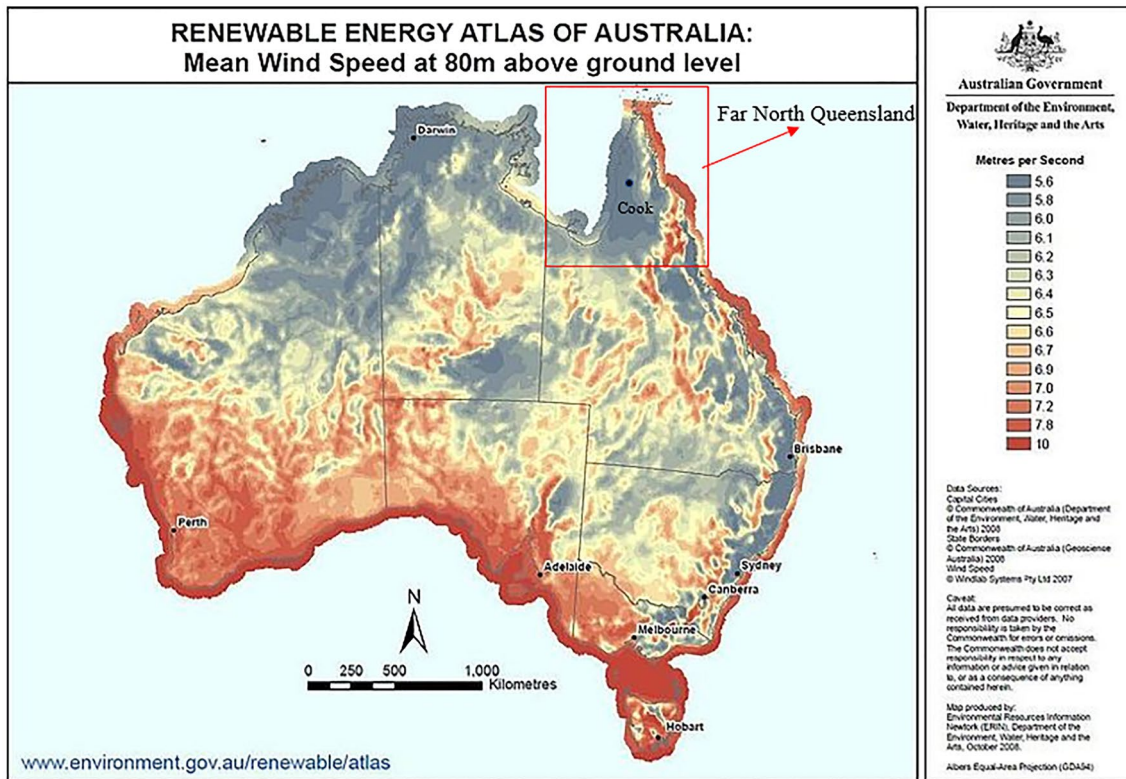
**Fig. 14** Mean wind speed at 80 m above ground level in Australia including FNQ [102]

**Table 2** GIS data set for identifying suitable locations

| Thematic theme | Type of data | Source | Spatial resolution |
| --- | --- | --- | --- |
| Administrative boundary | Vector | GADM, version 1.0 [117] | – |
| Water bodies | Vector | DIVA-GIS [117] | – |
| Protected areas | Vector | WDPA [118] | – |
| Airports | Vector | Data Share [119] | - |
| Urban built-up area | Vector | SEDAC [120] | – |
| Rail network | Vector | DIVA-GIS [117] | – |
| Road network | Vector | DIVA-GIS [117] | – |
| Land-use land cover | Raster | GlobCover [121] | 10 arcsec |
| Digital elevation model | Raster | CGIAR SRTM [117] | 30 s |

raster data. Then different GIS activities have been executed for each layer to fulfil the renewable energy development criterion, as described below:

(1) Extraction of land cover and digital elevation models of selected areas of FNQ from the land-use land cover and global digital elevation models, respectively, by utilising Extract by Mask tool.

(2) Extraction of slope model from the elevation model by Slope tool.

(3) Reclassification of raster model of a slope by Reclassify tool.

(4) Identification of suitable and unsuitable land cover from land cover data by Weighted Overlay tool.

(5) Conversion of all raster models into vector data set by Raster to Polygon tool.

(6) Implementation of a suitable buffer by Buffer tool on each layer that further expands the omitting criterion according to the assumptions considered in this study and merging unsuited layers by Merge tool.

(7) Removal of merged unsuitable areas from the suitable land cover (vector data) by Erase tool.

(8) Finally, the Clip tool is utilised to extract the administrative boundary of selected regions with the aid of the

**Fig. 15** GlobCover land-use land cover for selected regions of FNQ



Legend
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- 150
- 170
- 190
- 200
- 210
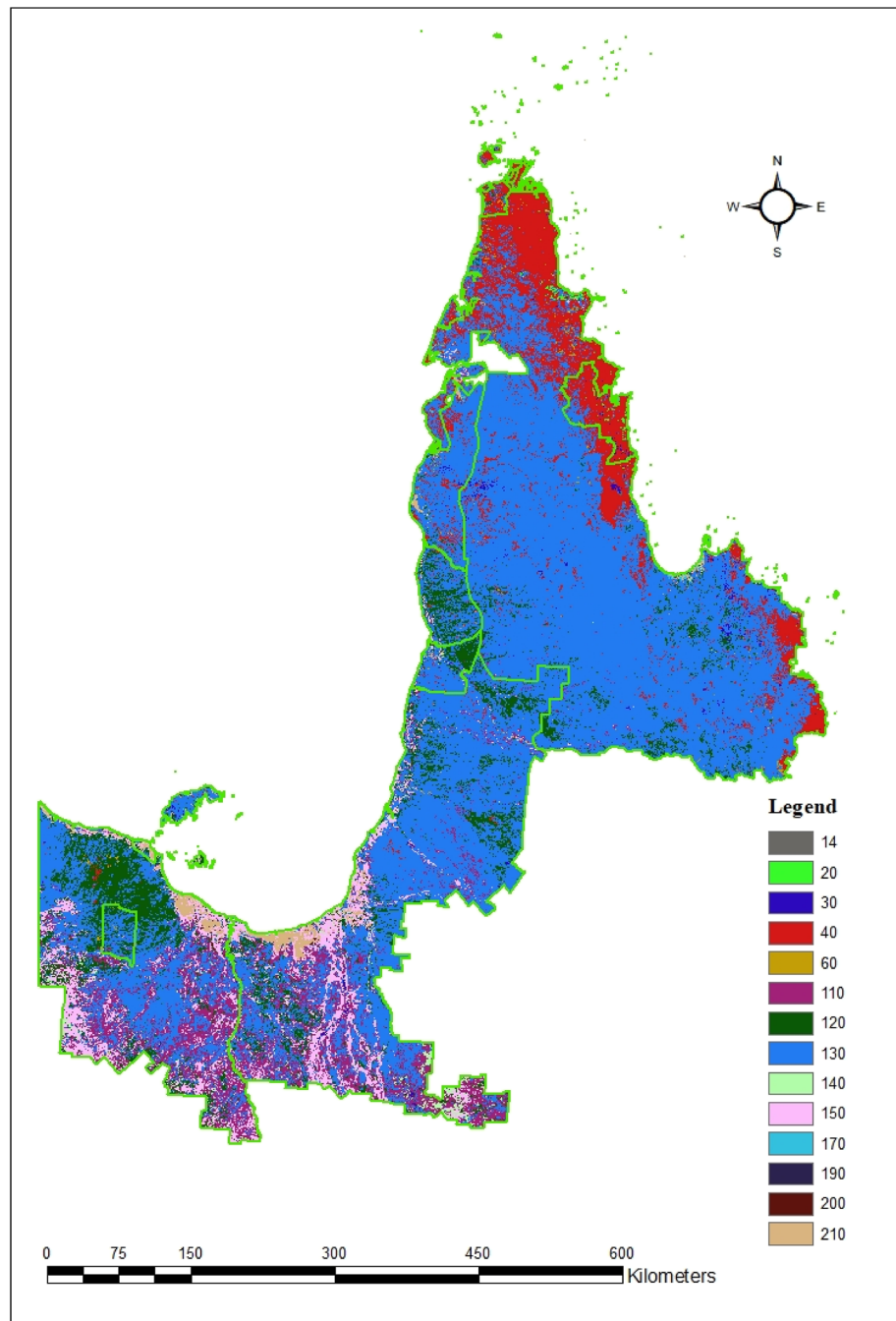
administrative boundaries of Australia from the final suitable layer.

At last, the total suitable places for each administrative boundary of the selected regions are acquired by computing their geometry in the attribute table. Based on the appropriate land-use factors, the maximal limits of solar and wind power generation capacity are evaluated for each selected region that illustrates the geographical potential of

renewable energy. Several exclusion criterion included for the assessment is outlined below:

(1) Land-use land cover (LULC): In this assessment, UN global land cover data are utilised. As per the criterion of a previous study [122], irrigated (class 11), rainfed croplands (class 14), mosaic cropland (class 20), shrubland (class 130), grassland (class 140), sparse vegetation (class 150) and bare areas (class 200) are considered suitable for wind plants. For solar, similar

**Fig. 16** Suitable land cover for solar in selected regions of FNQ
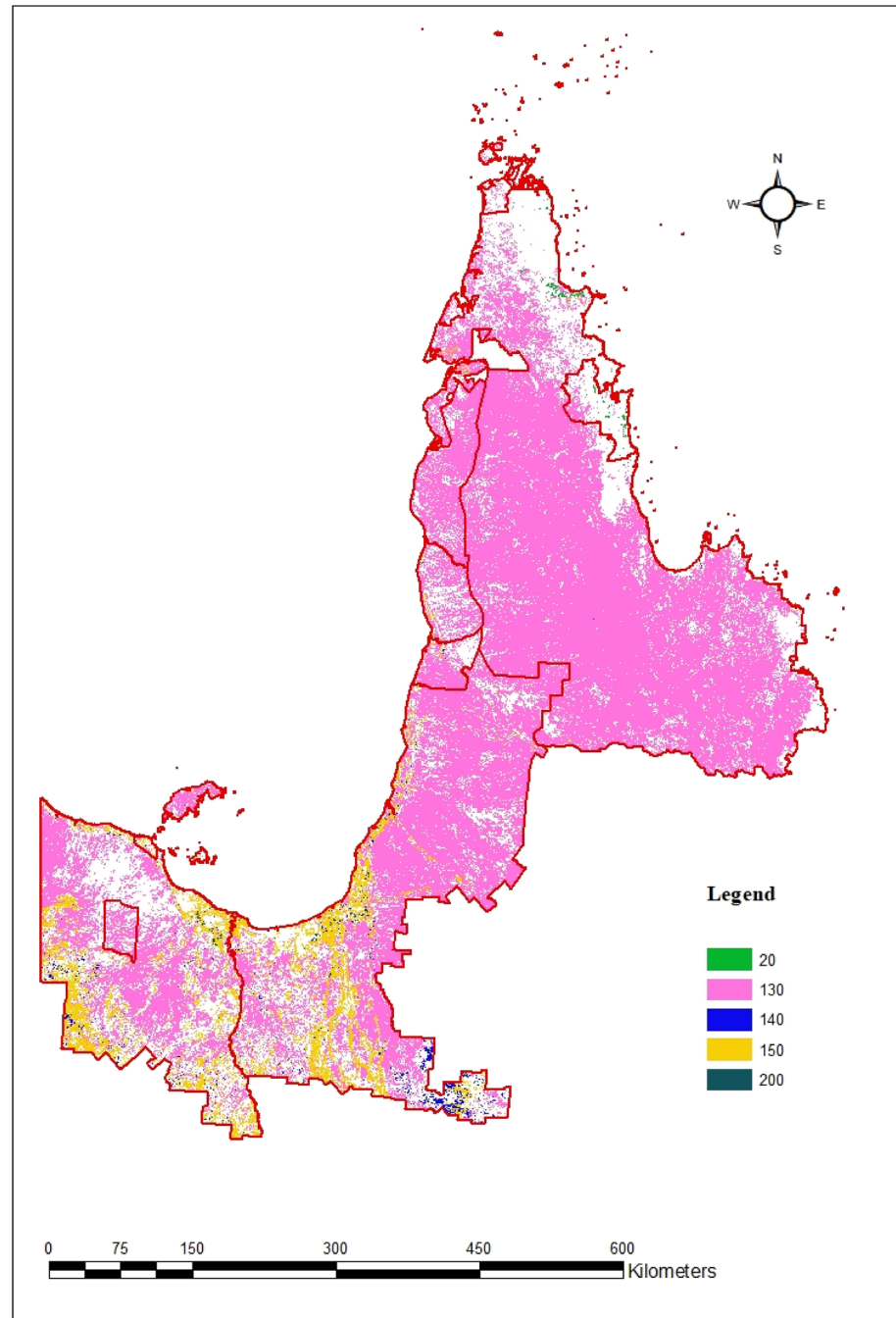


suitability criterion which is implemented for wind, is used, except irrigated (11), rain-fed croplands (14). Other land categories such as mosaic vegetation (class 30), broad-leaved deciduous (classes 50, 60) or semi-deciduous forest (class 40), needle-leaved ever green forest (classes 70, 90), mixed forest (class 100), mosaic forest (class 110) and grassland (class 120), woody wetlands (classes 160, 170), artificial areas (class 190), water bodies (class 210), snow or ice (class 220) are considered unsuitable for any power plant installation.

(2) Water bodies: In some studies, to conserve natural resources, reservoirs such as seas, rivers and lakes were omitted with a buffer of 100 m [123] and 400 m [109] for wind application; 400 m for both solar and wind application [103]. In this study, 400 m is considered for both solar and wind analysis.

(3) Protected area: Previous studies [124, 125] applied 1 km buffer for protected areas in wind application to preserve the protected areas such as world heritage sites, national parks and sanctuaries, which are not

**Fig. 17** Suitable land cover for wind in selected regions of FNQ
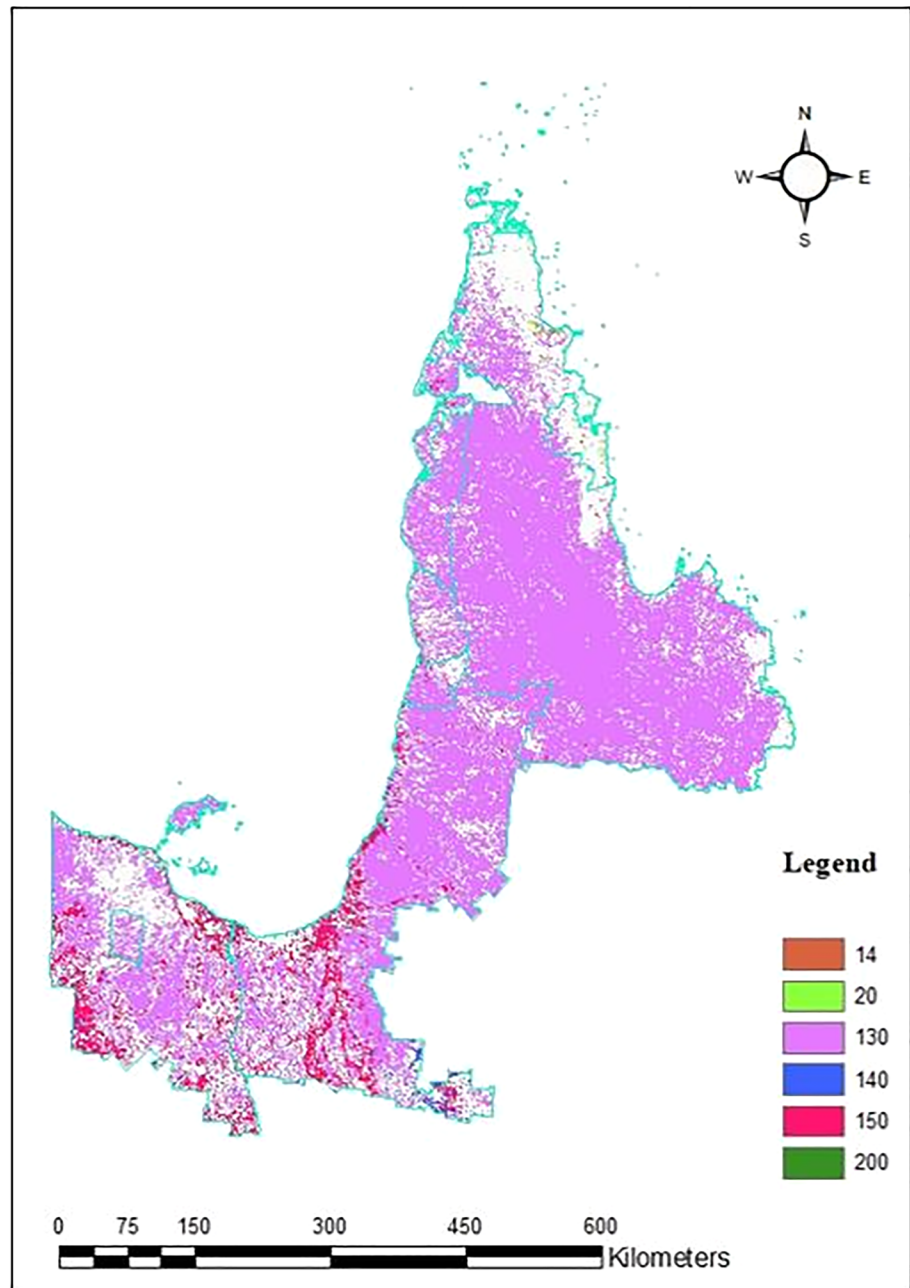


suitable for power plant installation. This study has adopted 1 km buffer for wind analysis.

(4) Urban and rural built-up area: In deploying renewable energies at a large-scale, densely populated and urbanised areas are not practicable for avoiding inconvenience to human life. Previous studies applied a buffer of 5 km [124] for wind applications, 500 m [126, 127] for solar and wind applications. This study has adopted 5 km buffer for wind analysis. And no buffer zone is applied for solar analysis.

(5) Rail and road network: Rail and road networks are not also practicable for renewable energy installation. Pre-vious studies applied a 300 m [124] buffer to road and rail networks considering their future expansion and a 500 m [128] buffer for reducing visual disturbance and ensuring electrical safety. In this study, 500 m buffer is maintained with existing rail and road networks for solar and wind analysis.

(6) Airports: In some studies [114, 129, 130], distance to airport is used for wind analysis, as wind turbines may disturb air traffic control by muddling the airport sur-veillance radar signals. Previous studies have imple-mented a buffer of 2500 m [104, 123] and 3000 m

**Fig. 18** Elevation of selected regions of FNQ
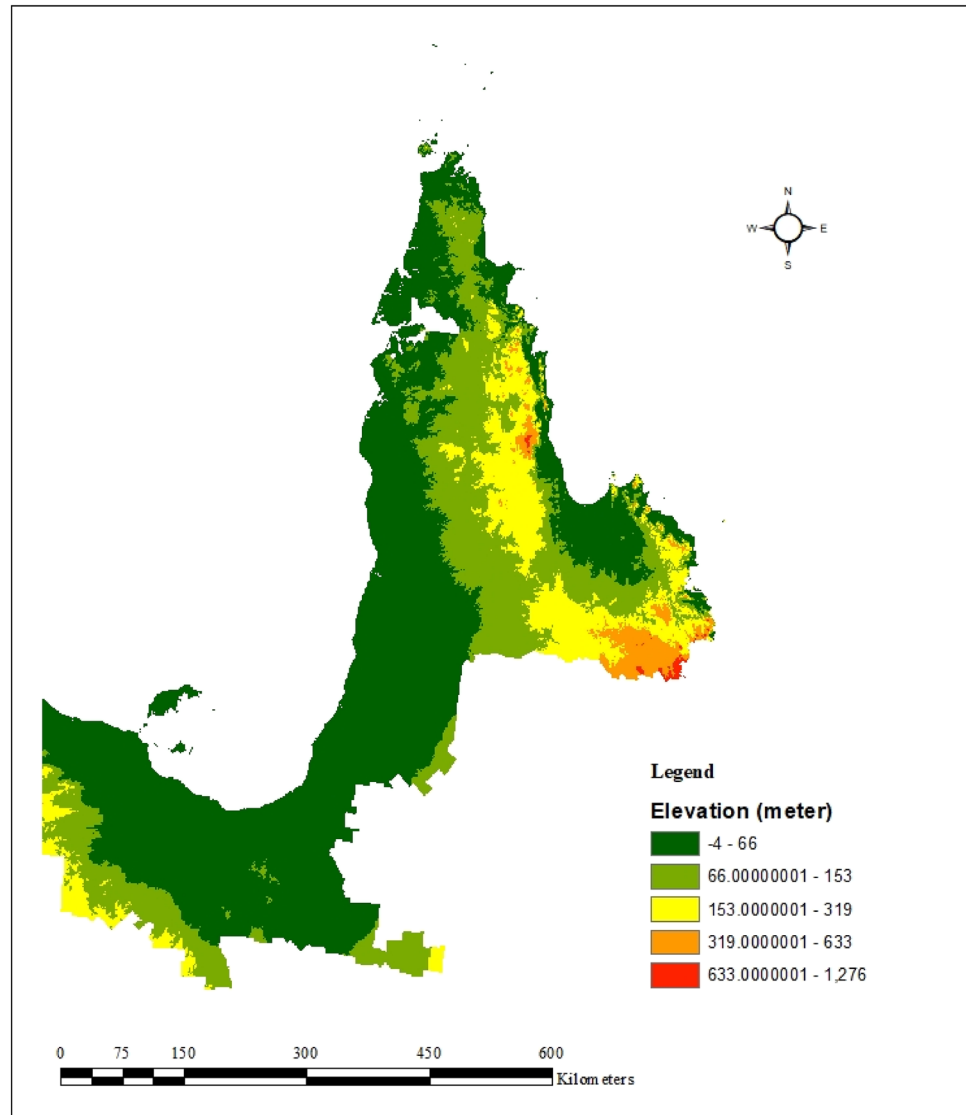
[129], and in this study, 3000 m is considered as a safer option.

(7) However, consultation is inevitable for installing any wind farm within a range of 30 km [131] of an airport. In the case of solar, glimpse and glint [132, 133] from panels may mystify pilots' vision and may also affect the radar systems. Hence, a 1000 m buffer is applied between airports and solar plant for the present study.

(8) Slope and elevation: Slope and elevation are the elementals of topography. Almost all studies recommend land with low slopes and low elevations for developing solar and wind projects [114, 126, 134, 135]. For wind projects, the allowable range of slope may vary within 10 to 30 degrees [134] and for solar can vary between 3 and 5 degrees [126, 134]. The elevation above sea level varies from place to place, and previous studies proposed elevation of 2000 m for solar and wind farms

[126, 136], 4500 m for solar farms [104], 2000 m for wind farms [128]. This study considers slope up to 5°for solar analysis and maximum 15° for wind analysis. From the slope map (as shown in Fig. 19), it is found that the selected regions of FNQ have maximum slope 14.82°. So, the slopes of the areas are fully suitable for wind power installation. Figure 18 represents the elevation of the regions. The maximum elevation is 1276 m, which is considered suitable for both solar and wind projects development.

## Results

The current study is the first ever work to explore suitable locations in FNQ for the development of solar and wind projects using GIS multi-criterion decision making. ArcMap 10.8.1 is used for GIS-based analysis. The assessment

**Fig. 19** Slope map for selected regions of FNQ
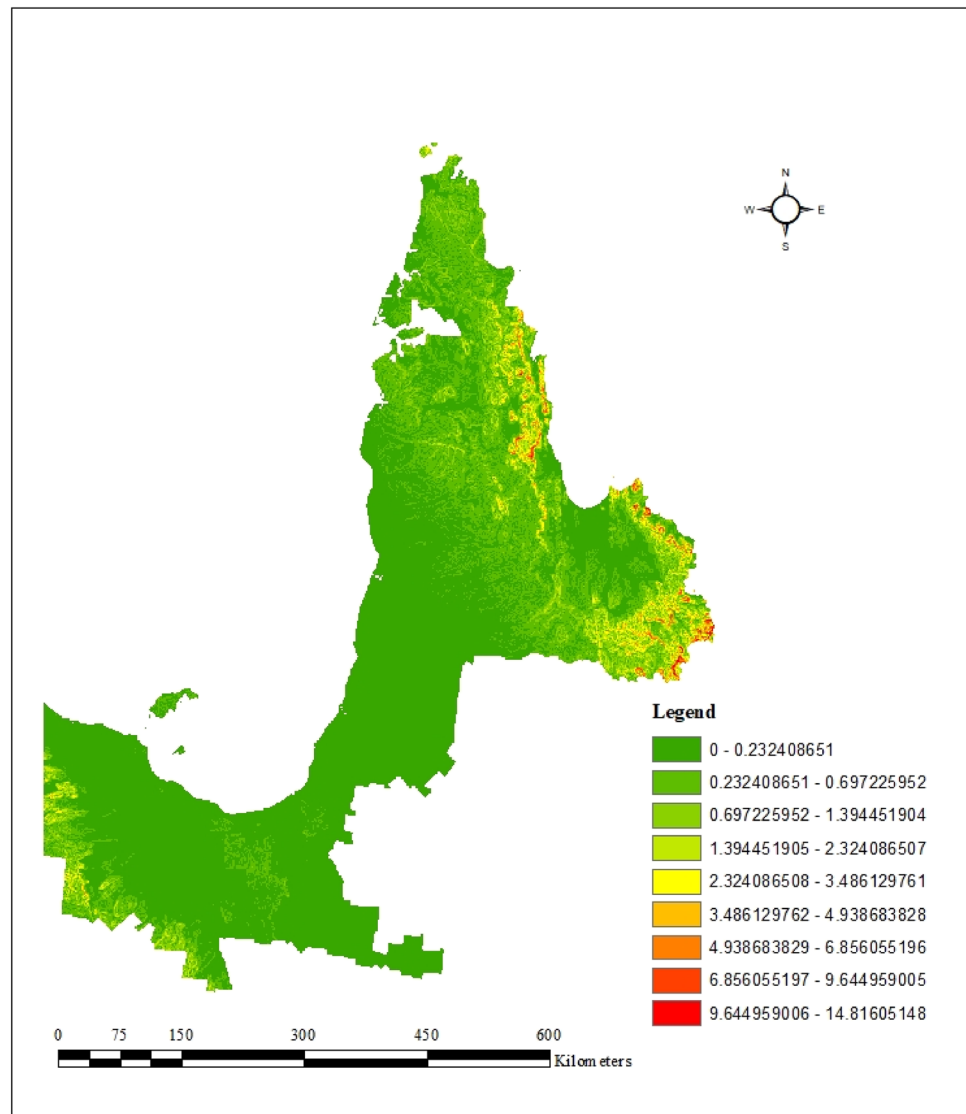


is conducted using GIS-based multi-layer approach. The outcome of different GIS activities executed for location suitability analysis, is displayed in Figs. 15, 16, 17, 18, 19, 20, 21. Figure 15 represents land cover information for the selected regions of FNQ such as classes 14 (rainfed croplands), 20 (mosaic croplands), 30 (mosaic vegetation), 40 (semi-deciduous forest), 60 (broadleaved deciduous forest), 110 (mosaic forest), 120 (mosaic grassland), 130 (shrubland), 140 (grassland), 150 (sparse vegetation), 170 (woody wetlands), 190 (artificial areas), bare areas (200) and water bodies (210). Figures 16 and 17 represent the suitable land cover for solar and wind, respectively, which are found after excluding unsuitable land cover. Figure 18 shows the elevation map. The elevation map shows that maximum areas of the selected regions are within −4 m to 66 m. Other areas have different ranges of elevation such as 66–153 m, 153–319 m, 319–633 m and 633–1276 m.

It is noticeable that the selected regions have a maximum elevation of 1276 m, which is well below previous studies' adopted elevation of 2000 m [126, 136]. So, the selected whole regions are considered suitable for both solar and wind. Figure 19 represents the slope map. From the slope map, it is seen that maximum areas of the selected regions have slope below 1.4° that means that maximum areas are almost flat and very much suitable for installing power plant. Few areas are within the range of 1.4° to 4.94°. Very few areas are within the range of 4.94–14.82°. The slope map is reclassified within the range of 0–5° and 5–14.82°, which is presented in Fig. 20. This figure has given more better understanding that almost all areas have a slope within 5°, which is suitable for solar. In addition, the maximum slope is 14.82°, so all the selected regions are fully suitable for wind, as this study adopts maximum 15° slope for wind analysis. Figure 21 represents the unsuitable GIS layers that include

**Fig. 20** Reclassified slope map for solar of selected regions of FNQ
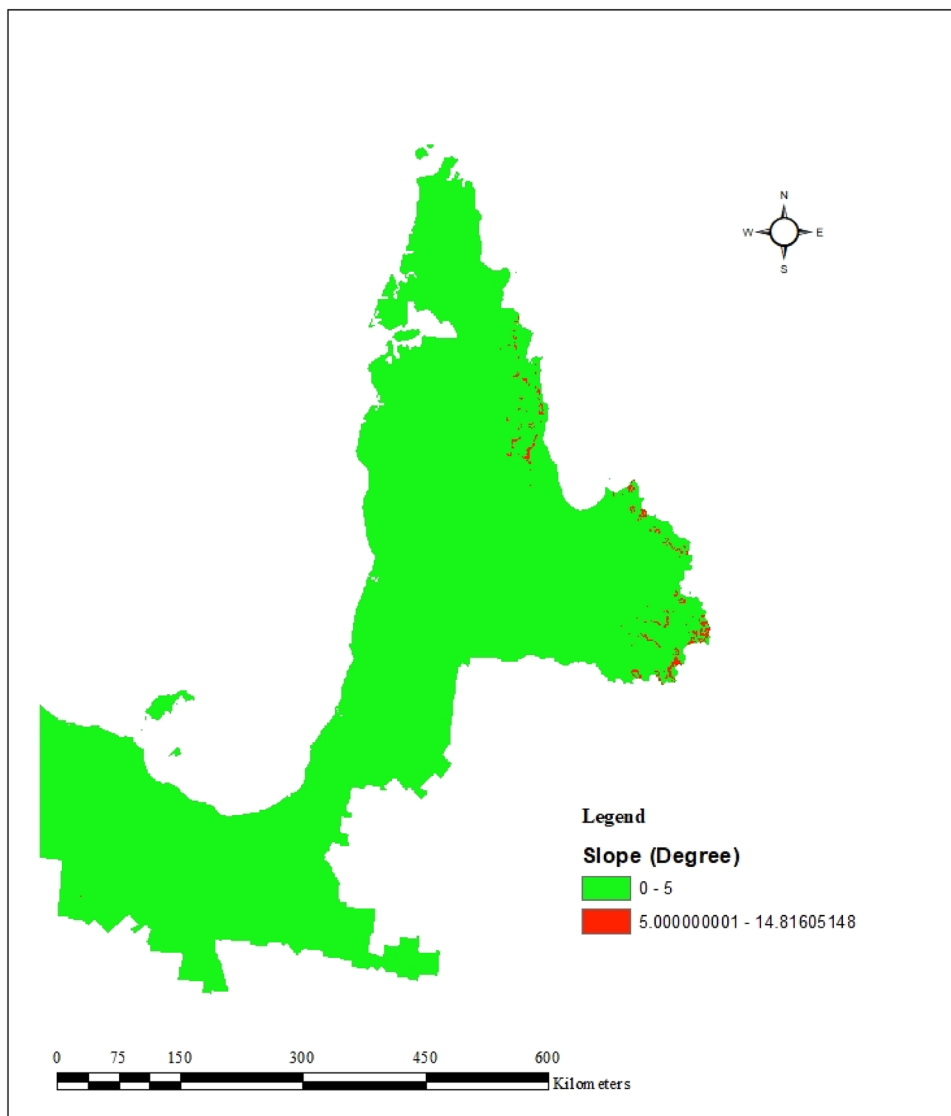


urban areas, protected areas, rail and road networks, water bodies and airports. Excluding these unsuitable layers with suitable buffer and considering suitable land cover, elevation and slope, final suitable places for solar and wind farms installation in selected administrative areas have been generated that are presented in Figs. 22 and 23, respectively. Suitable locations for solar and wind in every administrative region are calculated in the attribute table that are presented in Tables 3 and 4, respectively.

The suitable land evaluation process has been conducted for solar and wind separately. Initially, the selected regions are assumed only for being solar project and later only for wind project. Finally, the total land area suitable for solar power has been found to be 142,294.85 km$^2$ and for wind 144,563.83 km$^2$. The solar energy potential can be evaluated considering mean horizontal solar irradiation, suitable land

area and solar panel efficacy. Solar power potential can be calculated by the following equation [137]:

$$P_{\text{solar}} = G \times \text{SA} \times \text{AF} \times \eta \tag{1}$$

where $P_{\text{solar}}$ is the solar power potential, G is annual mean horizontal solar irradiation in kWh/m$^2$/day, SA is the suitable land area (m$^2$), AF is the area factor (%), and $\eta$ is the solar panel efficacy (%). Here, the area factor reveals the maximal places covered by the solar panels with minimal shadow effect. Area factor is considered 70% as used in the previous studies [113, 137]. Daily average solar irradiation data for selected regions are collected from Bureau of Meteorology. The study has used the First solar series 4™ PV module (advanced thin-film solar module), used in Kidston solar farm on the site of Kidston gold mine of FNQ. The maximum efficiency, 17%, of the module is used in this

**Fig. 21** Unsuitable GIS layers for selected regions of FNQ
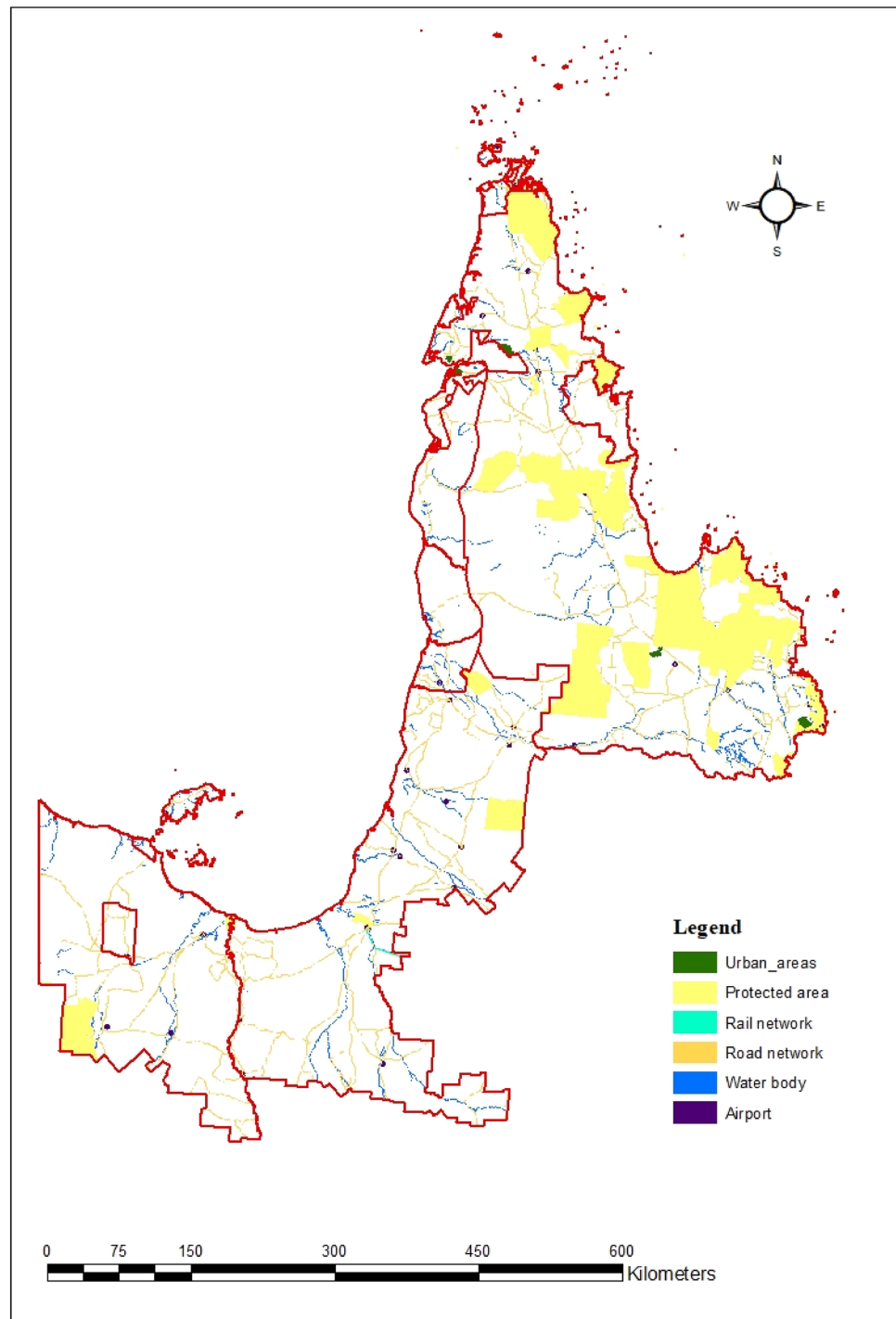


study to get the maximum possible solar power. Table 3 represents calculated solar power potential for the selected sites. The biggest area Cook is suitable for 6,107.30 GW solar power production, whereas the smallest area Umagico is suitable for 23.30 MW solar power production.

Wind power potential can be evaluated by the following equation [134]:

$$P_{\text{wind}} = \text{SA} \times \text{AF} \tag{2}$$

where $P_{wind}$ is the wind power potential (MW), SA is the suitable land area (m$^2$), and AF is the area factor (kW/m$^2$). In this study, wind turbines have been arranged at a distance of 7D×5D [113], where D is the rotor diameter. Area factor (AF) can be calculated as follows [134],

**Fig. 22** Final suitability map for solar power installation in selected regions of FNQ
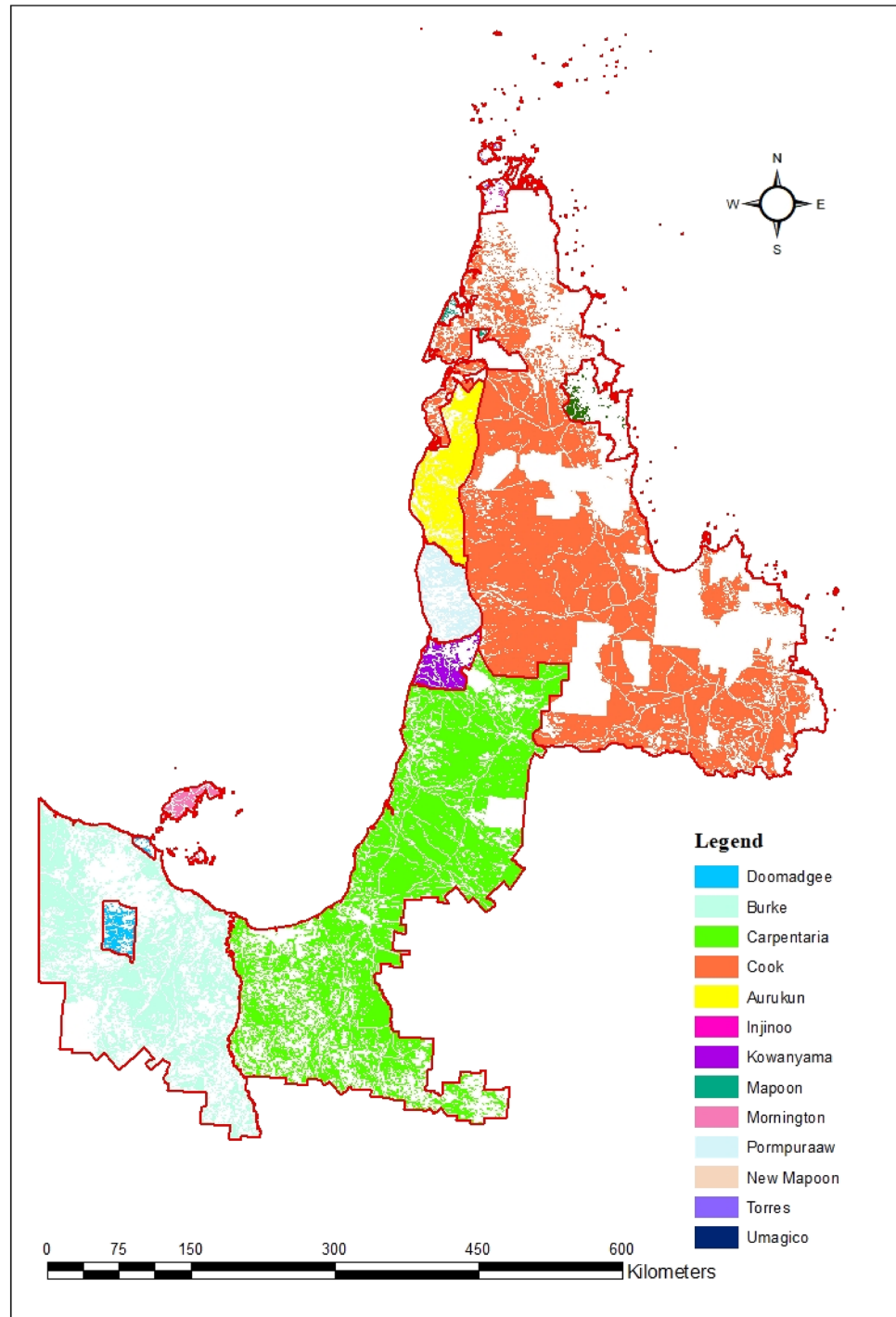


AF = Capacity/(7D × 5D)     (3)

The study has used Vestas V117-3.45 wind turbine specification to calculate wind power potential. The turbine capacity and rotor diameter are 3.45 MW and 117 m, respectively [138]. Table 4 represents calculated theoretical wind power potential for the selected regions. The biggest area Cook can be suitable for 450 GW wind power production,

whereas the smallest area Umagico is suitable for 1.38 MW wind power production.

## Economic potential

Another important thing is that renewable power generation cost needs to be cheap or cost competitive. According to Roam consulting Pty Ltd, compared to fossil fuel power

**Fig. 23** Final suitability map for wind power installation in selected regions of FNQ
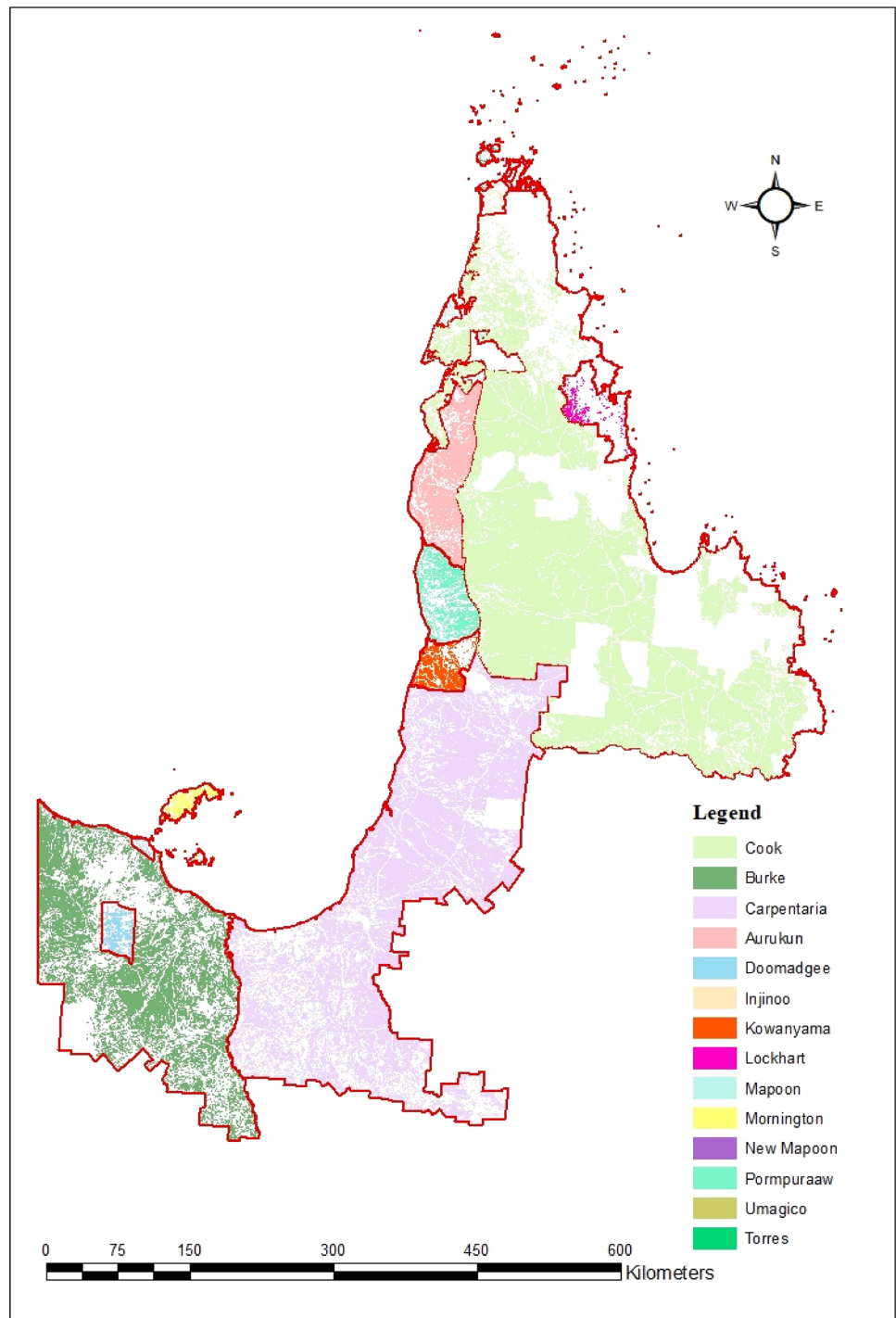


generation, renewable generation could be cheaper in the remote communities that would be advantageous and crucial for local economic growth. The Australian Climate Council [139] has reported that renewable power generation is the cheapest option now compared to new built coal and gas power generation, even with all of the existing subsidies associated with coal and gas. Table 5 depicts the power generation cost by sources [139].

**Table 3** Theoretical solar power potential

| Selected site | Annual solar mean radiation (G) (kWh/m²/day) | Suitable area (m²) | Theoretical power potential (MW) |
|---|---|---|---|
| Cook | 5.8 | 61,940,133,432.00 | 6,107,297.16 |
| Carpentaria | 6.1 | 45,689,555,002.00 | 4,738,006.85 |
| Burke town | 6.2 | 22,407,859,618.00 | 2,361,788.40 |
| Doomadgee | 6.1 | 1,049,736,835.00 | 108,857.71 |
| Mornington Island | 5.9 | 632,097,742.50 | 63,399.40 |
| Kowanyama | 6.1 | 1,546,394,148.00 | 160,361.07 |
| Pormpuraaw | 6.0 | 2,733,477,907.00 | 278,814.75 |
| Aurukun | 5.9 | 5,948,460,436.00 | 596,630.58 |
| Injinoo | 5.6 | 105,737,663.10 | 10,066.23 |
| Torres | 5.8 | 48,331,606.32 | 4,765.49 |
| New Mapoon | 5.7 | 1,264,375.11 | 122.52 |
| Umagico | 5.6 | 244,564.76 | 23.28 |
| Mapoon | 5.5 | 191,562,294.40 | 17,911.07 |
| Lockhart River | 5.6 | 521,935,891.28 | 347,818.08 |

**Table 4** Theoretical wind power potential

| Selected site | Suitable area (m²) | Theoretical power potential (MW) |
|---|---|---|
| Cook | 62,514,737,696.00 | 450,154.65 |
| Carpentaria | 46,115,274,994.00 | 332,065.78 |
| Burke town | 22,636,366,913.00 | 162,999.42 |
| Doomadgee | 1,035,985,866.00 | 7,459.90 |
| Mornington Island | 811,595,814.20 | 5,844.12 |
| Kowanyama | 1,581,502,920.00 | 11,388.05 |
| Pormpuraaw | 2,806,975,362.00 | 20,212.40 |
| Aurukun | 5,993,704,069.00 | 43,159.32 |
| Injinoo | 137,748,431.80 | 991.89 |
| Torres | 80,323,315.77 | 578.39 |
| New Mapoon | 1,288,902.50 | 9.28 |
| Umagico | 191,127.54 | 1.38 |
| Mapoon | 251,693,470.70 | 1,812.39 |
| Lockhart River | 596,438,879.30 | 4,294.82 |

**Table 5** Cost of new built power plants [139]

| Power technology | Levellised cost of energy (LCOE) $(aus)/MWh |
|---|---|
| Wind | $50–65 |
| Solar PV | $78–140 |
| Solar thermal plant | $78 |
| Gas combined cycle | $78–90 |
| Coal | $134–203 |
| Coal with carbon capture system (CCS) | $352 |

Recently, Queensland solar and wind projects show possibility to be the cheapest power generation option in Australia. For instance, the Coopers Gap wind farm of 453 MW in Queensland can deliver power with cost bellow $60/MWh [139]. Large-scale solar PV in Queensland has already reached bellow $80/MWh [140]. However, remote communities of FNQ have access to electricity, but emissions, cost and reliability are the major concern. They have to rely on expensive imported diesel. In 2018–19, the Queensland government [141] paid $465 million to Ergon Energy Retail for ensuring remote customers paid similar electricity prices to other users. Hence, many remote places are not paying the real cost of power supply. In addition, the utilisation of diesel-based power generation is contributing to environmental pollution such as noise, carbon emissions and oil spillage, high supply cost and increased road maintenance costs [141]. On the other hand, continued fall in the cost of solar and wind generation, including storage, can lessen the power supply cost and the need for diesel power generation [141]. The cost competitiveness of solar and wind open up the prospect of utilising local renewable energy resources in place of the existing diesel power generation system of FNQ. In addition, a vast deployment of renewable energy can fuel economic growth in FNQ, with creating new job opportunities, enhancing human well-being and eventually can contribute to a climate-safe future.

Queensland has a high ambitious target for installing renewable energy in FNQ, by expanding especially solar and wind energy resources. However, the installation of renewable power plant is very slow compared to their targets. The possible barriers may include lack of evidence of energy resources, poor infrastructure, high investment costs,

limited planning and lack of political motive. However, the results of the study can help various government agencies, policy and decision makers, researchers and parties in bringing renewables into the FNQ's energy system. The present study has performed a GIS-based analysis to assess favourable locations to develop two eminent resources, namely solar and wind. From the analysis, it is found that the FNQ has significant potential for exploiting solar and wind. Then the study has highlighted the LCOE or investment for solar and wind energy including conventional power systems, which proves that solar and wind resources have significant economic potential. The present study can give worthy guidance to the research community as well as potential parties regarding the location suitability to install solar and wind power stations. The current study assesses suitable places for solar and wind projects, including power potential, and presents an overview on economic potential. Hopefully, the results of the study will assist in attaining future renewable energy targets.

## Conclusion

Since the world progressively incorporates renewable power generation and switching away from expensive or emissions-intensive technologies, the demand is rising for hybrid renewable energy assets that combine multiple forms of generation and storage. Renewable energy sources are promising for eliminating ecological damage. From the technical and economic context, different methodologies have been developed to size and analyse techno-economic characteristics regarding renewable energy adoption. This study has presented a global survey on the renewable energy availability, development and an essential to implement renewable energy system within remote regions of Far North Queensland in Australia. This study has performed potential assessment for solar and wind resources in terms of climatic, geographical and economical. The assessment shows significant potential for solar and wind development in every aspect.

This study concludes that the selected areas from Far North Queensland are highly potential for solar and wind. The total maximum potential areas are found at 142,294.86 km$^2$ (55.94% of total selected areas) with power potential of 14,448 GW for solar and 144,563.80 km$^2$ (56.83% of total selected areas) with power potential 1040.97 GW for wind. Along with the solar and wind, hydrogen presents a clear perspective for a clean and affordable energy supply in the remote areas as well as deep decarbonisation which is the global target, needed to be reached by 2050 for limiting global surface temperature increment to 2 °C. In addition, the possibility to store hydrogen opens the opportunity for the integration of high renewable resources

(solar and wind) shares with positive effects on Australia's sustainable development goals through reduced GHG emissions. Hence, utilisation of renewable resources: solar and wind with water splitting hydrogen is the ultimate solution for energy system and sustainable ecology.

This study has presented a potential overview to the complexity of decision making in the renewable energy sector and a scientific basis for selecting efficient, cost-effective clean solutions for the energy system of remote communities of Far North Queensland, Australia. This knowledge will increase stakeholder confidence in investing in renewable energy, which will be integral to Australia's efforts to reduce reliance on dirty and costly diesel-based energy systems.

## Declarations

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