

ORIGINAL RESEARCH ARTICLE

Research on solar energy resource assessment and development pathway in Singapore

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ABSTRACT

Solar energy is the only renewable energy source likely to be developed on a large scale in Singapore. Singapore has limited land resources. According to the land use, the solar energy exploitable areas can be divided into five categories: rooftop photovoltaic, building surface photovoltaic, land-based photovoltaic, floating photovoltaic and infrastructure photovoltaic. The total development area of each type of photovoltaic is about $3,680 \times 10^4 \text{ m}^2$. According to the assessment, Singapore has about $968 \times 10^4 \text{ kW}$ in 2050, of which distributed solar energy accounted for about 74%. Roof, building and infrastructure photovoltaic mainly adopt distributed development with high cost of per kWh; land-based and floating photovoltaic mainly adopt centralized development with low cost. According to the cost reduction speed and development degree of various kinds of solar energy, two solar energy development paths from 2030 to 2050 are proposed, namely, the full development path and the economic development path. The full development path aims at the full development of solar energy potential, and the economic development path considers the kilowatt-hour cost of solar energy development. The difference between the two paths focuses on the development degree of rooftop photovoltaic and building surface photovoltaic. Under the full development path, the electrification level reaches 61%, 16 percentage points higher compared with the economic development path; the installed renewable energy capacity reaches 51%, 19 percentage points higher compared with the economic development path. On the basis of two solar energy development paths, two 2050 energy scenarios adapted to different solar energy development paths are proposed. Singapore is unable to be carbon neutral in either development path or needs to increase transnational transmission.

Keywords: Solar Energy Resources; Photovoltaic; Full Development; Economic Development; kWh Cost; Singapore

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1. Introduction

Singapore is a world-famous “pocket-size” developed country, short of fossil energy resources, but it takes advantage of its geographical advantages to embark on the road of export-oriented energy rich country with crude oil processing as the core. Aiming at urban greening, sustainable living and a green economy, Singapore has completed the transition from oil to natural gas in the past 50 years, and achieved clean electricity. With the climate change challenges of global warming, how to reduce carbon emissions and achieve carbon neutrality has become the focus of the Singapore government and research institutions. Developing renewable energy is an important measure to achieve carbon neutrality, but Singapore lacks renewable energy, without any hydro and geothermal resources. In terms of wind energy, except for coastal areas and offshore islands, the average wind speed is generally less than 2 m/s, and most coastal areas are used as

ports, moorings and waterways, so there is little potential for wind resource development. Solar energy is the most promising renewable energy source in Singapore, with an average annual irradiation intensity of 1,600 ~ 1,700 kW·h/m². Development of solar energy is the most viable renewable energy option in Singapore^[1-7]. With solar energy as the core, this paper evaluates various types of solar energy exploitable resources in Singapore, calculates the cost changes of various types of solar energy, and gives two solar energy development paths of full development and economic development, as well as the Singapore 2050 energy scenario outlook to adapt to different solar energy development paths.

2. Assessment of solar energy resources

2.1 Assessment of developable area

Singapore has limited land resources, less land to build large-scale photovoltaic bases, and requires full use of various photovoltaic areas that can be developed. Based on land use, Singapore solar developable areas can be divided into the following five categories: rooftop, building surface, land-based, floating and infrastructure PV.

2.1.1 Rooftop PV

The assessment of the potential is based on a detailed 3D urban model of the Singapore Bureau of Land Management (SLA), which includes all 158,000 buildings in Singapore. After removing buildings with very small available surfaces (less than 10 m², not available for PV deployment), about 132,000 buildings participated in the assessment of rooftop PV development potential, with a total roof area of about 9,870 × 10⁴ m². After the minimum irradiation amount, maximum inclination, minimum continuous area and building type screening, the total area of rooftop photovoltaic that can be developed is about 1,322.1 × 10⁴ m², among which residential housing area is about 222.5 × 10⁴ m², industrial building area is about 805.6 × 10⁴ m², commercial building area is about 165.6 × 10⁴ m², and buildings with other purposes area is about 128.4 × 10⁴ m².

2.1.2 Building surface photovoltaic

The assessment of photovoltaic development potential on building surfaces is similar to the roof, based on the detailed 3D urban model of the Singapore Bureau of Land Management (SLA). The assessment includes all facade areas suitable for PV installation, regardless of the degree of integration of the building, that is, the building added PV (BAPV) and the building integrated PV (BIPV). The total area involved in the evaluation of the building surface is 2.14 × 10⁸ m². After minimum irradiation, minimum continuous area, building window to wall ratio and surface orientation screening, the surface photovoltaic exploitable area of the existing building is about 787.7 × 10⁴ m². Based on the average number of new buildings in Singapore over the past 10 years, 100 new buildings per year will be about 195 × 10⁴ m² by 2050.

2.1.3 Land-based PV

Assessment of the land-based PV exploitable potential is based on the vacant land information system of Singapore Bureau of Land Management (SLA), and the assessment area includes vacant land on Singapore's main island and two larger islands that may be connected to the main island grid—Jurong Island and Pulau semakau Island. When assess whether it can be used for solar deployment, considering public acceptance, conflicts of interest, and economy, excluding fields, forests, nature reserves, unsuitable debris areas, and land reclamation areas. The total exploitable area of land-based PV is about 500 × 10⁴ m², of which 35 × 10⁴ m² is the main island, Jurong Island 380 × 10⁴ m² and Pulau semakau Island 85 × 10⁴ m². Most of the exploitable areas are concentrated in on Jurong Island^[8].

2.1.4 Floating PV

Floating PV refers to the installation of solar photovoltaic systems on water bodies, and the assessment of the exploitable potential includes floating PV in inland water bodies and offshore waters. Singapore's total inland water area is about 6% of its total territory, but due to various restrictions, only a small fraction of them can be used for floating photovoltaic deployment. After

evaluation, the total area of solar photovoltaic power generation can be about $400 \times 10^4 \text{ m}^2$. After deducting the waters designated to maintain buoys and safe buoys, the net photovoltaic area is about $250 \times 10^4 \text{ m}^2$. Because Singapore's offshore space is very crowded, only areas known as the "Dead Sea space" are included in the assessment, excluding environmental requirements such as biodiversity, with about $211.6 \times 10^4 \text{ m}^2$ ^[9].

2.1.5 Infrastructure and photovoltaic power

Infrastructure photovoltaic refers to the combining of existing infrastructure with a solar

photovoltaic system without interfering with the original use of the land. The infrastructure included in the assessment includes land (open parking lots, agricultural areas, etc.), sound insulation barriers, flood control channels, roads, etc. Through new technical transformation such as 3D space expansion of existing infrastructure, about $415 \times 10^4 \text{ m}^2$ can be used to install photovoltaic, including $250 \times 10^4 \text{ m}^2$ land, $100 \times 10^4 \text{ m}^2$ sound barrier, $25 \times 10^4 \text{ m}^2$ flood control channel, and road about $40 \times 10^4 \text{ m}^2$ ^[10]. The exploitable area of various types of PV in Singapore is shown in **Table 1**.

Table 1. Developable area of all types of PV in Singapore

Solar type	Subclass	Developable area/ 10^4 m^2
Rooftop photovoltaics	Houses for residents	222.5
	Industrial buildings	805.6
	Commercial buildings	165.6
	Others	128.4
Building surface photovoltaics	Building renovation	787.7
	New buildings	195.0
Land-based photovoltaics	The island	35.0
	Jurong Island	380.0
	Pulau semakau Island	85.0
Floating photovoltaics	Inland	250.0
	Offshore	211.6
Infrastructure photovoltaics		415.0
Total		~ 3,680

2.2 Assessment of the exploitable potential

Based on the exploitable area of various types of solar energy to predict the area coefficient of the future PV system, then the exploitable potential of Singapore can be evaluated. In 2020, the most advanced photovoltaic panel area coefficient can reach 0.19 kW/m^2 . According to the forecast of international Solar Energy Organization, the photovoltaic system area coefficient can reach $0.25 \sim 0.3 \text{ kW/m}^2$ ^[11] in 2050. The land-based photovoltaic area coefficient is taken as 0.3 kW/m^2 , other types are measured as 0.25 kW/m^2 . the developable PV potential in 2050 is about $968 \times 10^4 \text{ kW}$, among them, rooftop photovoltaic has the greatest development potential, approximately $330 \times 10^4 \text{ kW}$, accounting for 34%; the exploitable potential of building surface PV is about $246 \times 10^4 \text{ kW}$, accounting for 25%; the land-based PV $150 \times$

10^4 kW , accounting for 16%; the floating photovoltaic PV $138 \times 10^4 \text{ kW}$, accounting for 14%; the infrastructure photovoltaic $104 \times 10^4 \text{ kW}$, accounting for 11%. The exploitable potential of various PV products in Singapore is shown in **Table 2**.

3. Solar kWh cost

3.1 Prediction method of kWh cost

3.1.1 Calculation model

The levelized cost of energy (*LCOE*) is calculated in equation (1). The numerator is the project cost in the whole life cycle, including equity investment capital cost (*EPCI*), operating cost (*OM*), insurance (*IC*), inverter warranty extension cost (*IEI*). The year of the extended warranty depends on the inverter supplier, and the model assumes a warranty period of 20 years. The Loan (*LP*)

includes annual interest and amortization. The OM , IC , and IEI adjust for inflation rates after the first year. The denominator is the full life-cycle power generation of the system. The power generation in the first year of the system is calculated by

$$LCOE = \frac{EPCI + \sum_{n=1}^N \frac{OM^* + IC^*}{(1 + DR)^n} + \frac{IEI_{n=5,10,15,20}^*}{(1 + DR)^{n=5,10,15,20}} + \sum_{n=1}^N \frac{LP}{(1 + DR)^n}}{\sum_{n=1}^N \frac{(IRD \times RP) \times (1 - SDR)^n}{(1 + DR)^n}} \quad (1)$$

The numerator and denominator are discounted by the nominal discount rate (DR) calculated from the net present value of the Weighted Average Cost of Capital ($WACC$).

available irradiance (IRD) and performance ratio (PR). After the first year, the power generation is adjusted annually according to the system decline rate (SDR).

$$WACC = (1 - D) \times (RFR_{20} + b \times MRP) + D \times (RFR_{10} + DP)(1 - TR) \quad (2)$$

Table 2. Developable potential of various photovoltaics in Singapore

Solar type	Subclass	Developable potential/10 ⁴ m ²
Rooftop photovoltaics	Houses for residents	56
	Industrial buildings	201
	Commercial buildings	41
	Others	32
Building surface photovoltaics	Building renovation	197
	New buildings	49
Land-based photovoltaics		150
Floating photovoltaics	Inland	75
	Offshore	63
Infrastructure photovoltaics		104
Total		968

The local risk-free interest rates (RFR) are based on Singapore government bond yield data, the cost of debt is 10 years (RFR_{10}), and the equity cost is 20 years (RFR_{20}). The cost of equity assumes that investment in solar systems shares the same risk with investment in the Singapore economy, the beta coefficient (b) is 1.0. The market risk premium (MRP) is calculated using the latest data from the Singapore National Electricity Market (EMA); the Debt ratio (D) is the percentage of an investment financed by an external lender; debt surcharge (DP) takes 3.07%; tax rate (TR) using the income tax rate of Singapore enterprises, 17%.

3.1.2 Basic assumptions

To simplify the calculation, following assumptions are made:

(1) **The investment cost.** Due to space constraints, the inefficient modules (polysilicon modules or below or equal to 300 W) is no longer taking into consideration; and the minimum cost of

photovoltaic module, central inverter and string inverter are set as 0.10 USD/W, 0.025 USD/W and \$0.035/W respectively^[12]. Excluding solar grid connection and transmission costs; and to simplify analysis, excluding surplus value and decommissioning costs, assuming they are in balance.

(2) **The operating costs.** Excluding any rent fees; operating and maintenance costs range from 1% to 1.45% of capital expenditures, depending on system type (large size roof is 1%, small size is 1.45%). As capital expenditure decreases over time, the insurance cost is estimated to be between 0.4% and 0.6% of the capital expenditure. Based on the empirical data from the National Environment Agency of Singapore (NEA)^[13], And the monthly data from 1991–2000 and 2010–2018, assuming that the constant annual irradiance of P50 is 1,644 kW·h/m². The performance ratio starts at 78%, and move up at 0.5% a year, until the upper limit of

82% of monocrystalline silicon is reached. Assuming that the performance ratio of floating PV system increases by 6% compared with rooftop PV and land-based PV systems^[14]; the system decline rate remains constant throughout the forecast period, roof and land-based photovoltaic systems were 0.8%, inland reservoir floating photovoltaic power is 1%, offshore floating photovoltaic power is 1.5%.

3.1.3 Selection of basic financial parameters of the model

The loan term is 10 years; using a 25-year linear depreciation; the system life span is 25 years; operating costs (OPEX) inflation rate is 1.7%; no tax is included; no interest was available during the construction period, assuming that the lender provides a grace period; fixed exchange rates throughout the forecast period, 1 USD for 1.36 SGD; nominal debt ratio of 5% (risk-free interest rate of 1.92%, debt premium of 3.08%); equity cost of 8.75% ~ 9% (risk-free rate of 2.22%, market risk

premium of 6.53%, Beta factor of 1.0); 100% equity financing WACC = 9%.

3.2 Change forecast of kWh cost

According to the evaluation, the *LCOE* changes of various PV types from 2025 to 2050 are shown in **Figure 1**. In 2025, the land-based photovoltaic *LCOE* was 0.08 SGD/(kW·h), which is equivalent to the cost of gas and electricity, while the cost of other photovoltaic types is still high, between 0.12 and 0.19 SGD/(kW·h).

In 2030, land-based PV *LCOE* continued to fall to 0.054/(kW·h); inland floating PV *LCOE* fell to 0.07/(kW·h); rooftop PV, building surface PV, offshore floating PV and infrastructure PV *LCOE* remains high at 0.09 ~ 0.11/(kW·h).

In 2050, land-based PV and inland floating PV *LCOE* fell to 0.05/(kW·h); offshore floating PV and infrastructure PV *LCOE* both fell to 0.076/(kW·h); roof and building surface PV to 0.09/(kW·h) and 0.105/(kW·h) respectively.

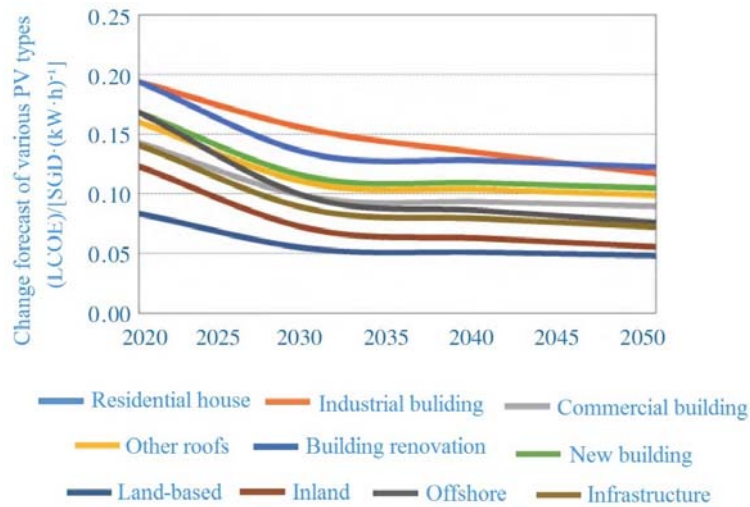


Figure 1. LCOE change prediction of various PV types from 2025 to 2050.

3.3 Path prediction of solar energy development

The path of solar energy depends not only on the rate of cost decline, but also on the government's attitude towards it. At present, Singapore Energy Market Authority plans to reach the solar installed capacity of 200×10^4 kW by 2030, but the medium and long-term development plan for solar energy is not clear, and it is difficult to give a clear solar energy development path according to existing policies and relevant data.

Therefore, in view of the policy uncertainty, this paper gives two solar energy development paths from 2030 to 2050, namely, the full development path and the economic development path.

3.3.1 Fully development path

On the basis of the installed solar capacity of 200×10^4 kW by 2030, the solar potential will be basically developed by 2050, and the installed solar capacity will reach 900×10^4 kW. The development order begins with the economic

solar types based on *LCOE*, the development focuses on land-based photovoltaic by 2030, inland floating photovoltaic, infrastructure photovoltaic and a small number of rooftop photovoltaic by 2040, all types of solar energy development completed by 2050. The changes of solar energy installed capacity from 2030 to 2050 under the full development path are shown in **Figure 2**.

3.3.2 Economic development Path

On the basis of the plan of the solar installed capacity to reach 200×10^4 kW in 2030, the development of certain economic solar energy begins. When the *LCOE* of solar energy falls to 0.08 SGD/(kW·h), the development of this kind of solar energy begins. It is predicted that the solar installed capacity will reach 600×10^4 kW by 2050. The development plan concentrates on land-based PV by 2030, land-based photovoltaic, infrastructure photovoltaic and inland floating photovoltaic by 2040, and full development of land-based photovoltaic, infrastructure photovoltaic and

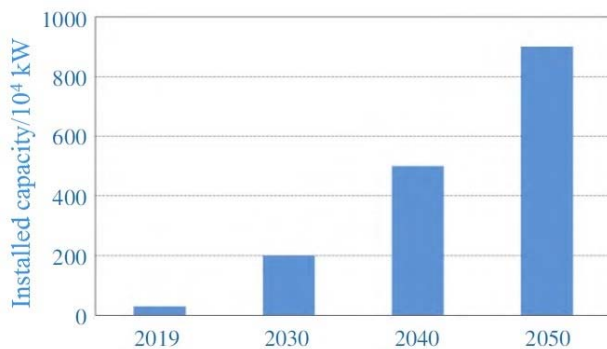


Figure 2. Changes of solar energy installed capacity—full development path.

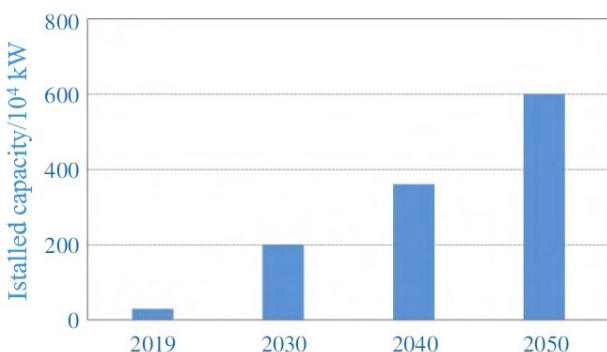


Figure 3. Changes in solar energy installed capacity—economic development path.

floating photovoltaic by 2050. A small amount of rooftop photovoltaics will be developed, and wall photovoltaics will be developed on a pilot basis. It

is estimated that the total cost of solar energy development is only half of the full development path. The changes of solar energy installed capacity from 2030 to 2050 under the economic development path are shown in **Figure 3**.

The comparison of two solar development paths is shown in **Figure 4**. By 2050, the development of land-based photovoltaic, infrastructure photovoltaic and floating photovoltaic will be basically completed, and the difference between the two development paths focuses on the development degree of rooftop photovoltaic and building surface photovoltaic. Due to the high cost of rooftop photovoltaic and building surface photovoltaic kWh, it is difficult to conduct large-scale centralized development. In the economic development path, the development of rooftop photovoltaic will only be carried out in the pilot form from 2030 to 2040, and from 2040 to 2050, cheaper industrial rooftop photovoltaic will be developed and the pilot development of building photovoltaic will be carried out.

4. 2050 energy scenario outlook for different solar energy development paths

4.1 Scenario construction method

On the basis of the development of the two solar energy paths, according to the consumption of renewable energy, the decommissioning of gas and power units and the transnational Internet situation, the two energy and power development scenarios are obtained, including the full development scenario of renewable energy and the economic development scenario of renewable energy. These two scenarios are discussed, and the specific path of energy and electricity development in Singapore is given in two extreme scenarios, comparing the energy structure, power structure, cost difference and interconnection degree of the two extreme scenarios.

Constraints for the two scenarios include the Singapore 2030 Energy and Power Plan, renewable energy installations following their own solar energy development path, power balance and energy terminal consumption balance.

The development goal of the full development scenario of renewable energy is to achieve the highest proportion of renewable energy as possible. In order to achieve the goal, no restraints to the transnational channel capacity, energy structure changes, and gas-power units will only serve for 30 to 40 years. The development goal of the economic development scenario of renewable energy is to

keep cost as low as possible. In order to achieve the priority of self-sufficiency of target power of, existing industries are not electrified (the new part is not limited), and gas power units are in service for 50 years. The constraints and development goals for the two energy scenarios in Singapore are shown in **Figure 5**.

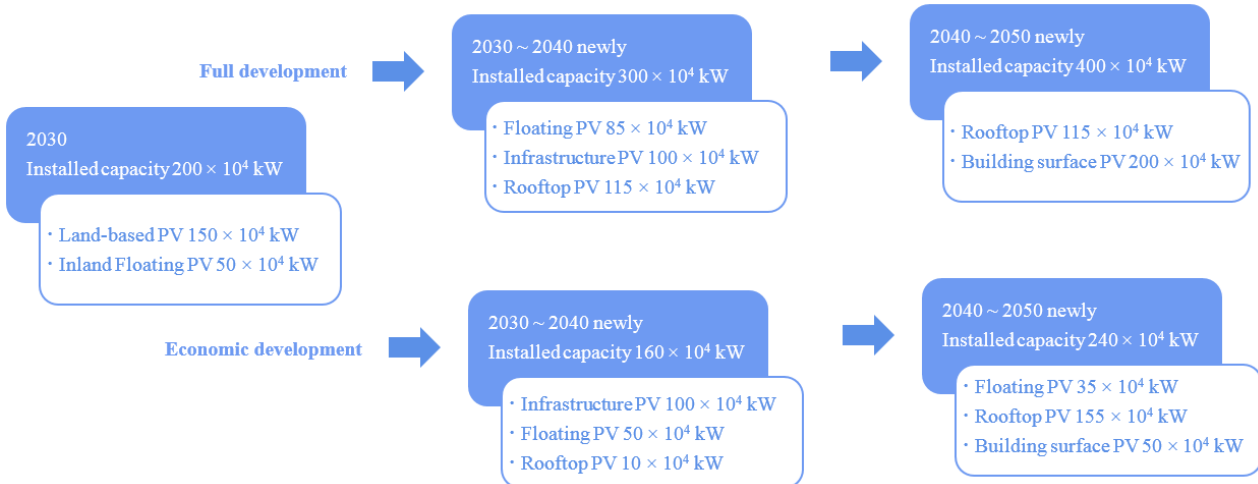


Figure 4. Comparison of solar energy development path.

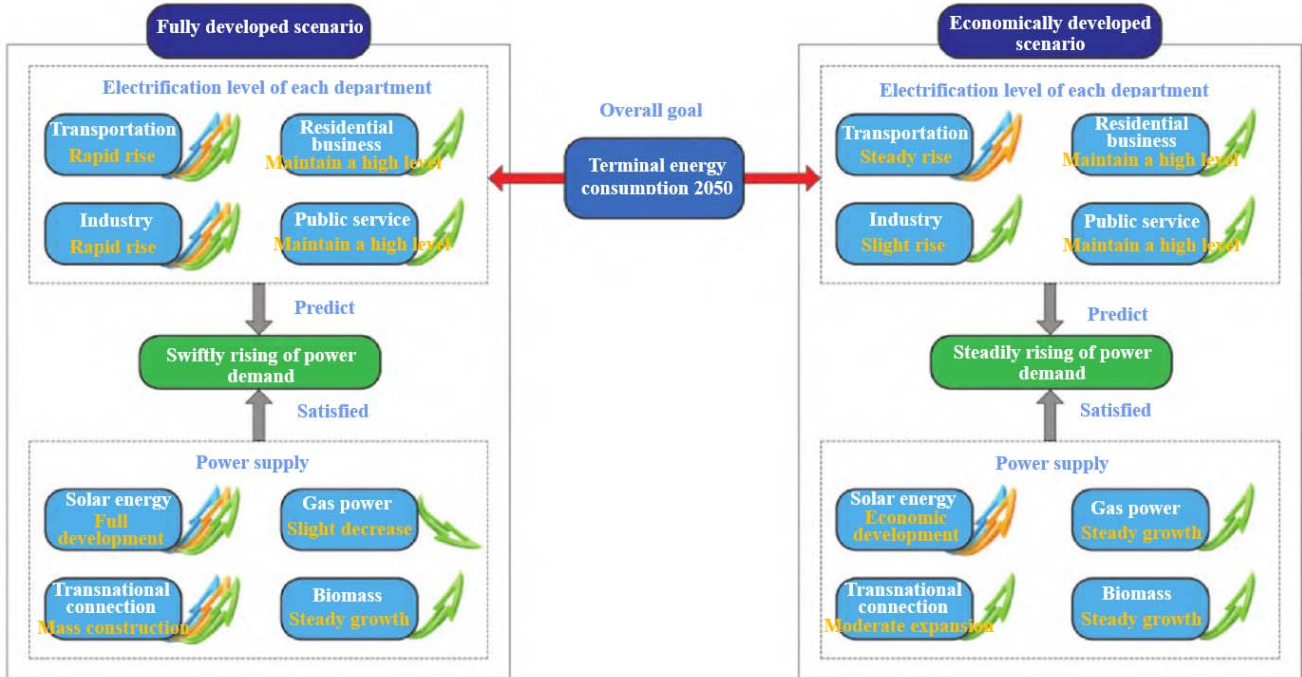


Figure 5. Constraints and development goals for the two energy scenarios.

4.2 Full development scenario solar energy

4.2.1 Energy transformation mode

The transportation department considers the electric energy replacement for fuel vehicle such as cargo vehicles, and aircraft and ships are not considered. The calculation equation of the terminal

energy electrification rate in the transportation department is shown in the equation (3).

$$I = \frac{E_{EV}}{E_{EV} + E_{FV} + E_{Others}}$$

$$E_{EV} = M(1 + r_V)^n \cdot R_{EV} \cdot L \cdot K_E$$

$$E_{FV} = M(1 + r_V)^n \cdot (1 - R_{EV}) \cdot L \cdot K_F \quad (3)$$

In the equation: I is the terminal energy electrification rate of the transportation department; E is the energy consumption of various transportation terminals, for example, E_{EV} is the terminal energy consumption of electric vehicle, while E takes the energy consumption of plane, ship and other transportation terminals in 2020, assuming it is constant; M is the total existing vehicles; r_V is the annual vehicle growth rate; n is the growth year, for example, if 2050 is the target year, then n is 30; R_{EV} is the target annual electric vehicle ratio; L is the average vehicle mileage; K is the terminal energy consumption per unit mileage.

According to the data of Singapore Land Transport Authority (LTA), the number of cars in Singapore was about 600,000 in 2018. Limited by land resources and road tolerance, the annual growth rate of Singapore cars will not exceed 0.2% in the future^[15-17]. It's estimated that the share of electric car in Singapore will be 30% by 2030, with more than 200,000 vehicles. Under the full development path, the electric car in Singapore will account for 80% by 2050, with more than 500,000 vehicles, and electricity will account for 55.8% of energy consumption in the transportation sector, as shown in **Figure 6**.

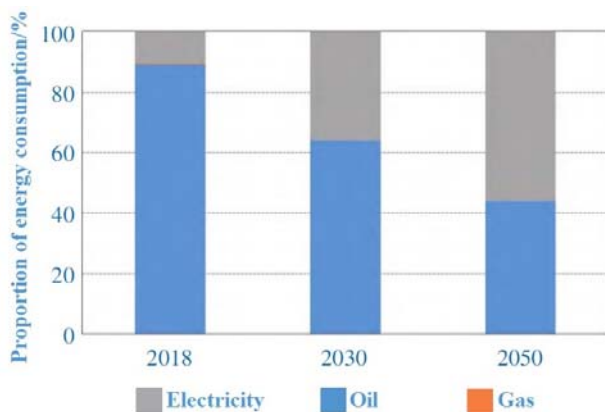


Figure 6. Energy consumption change in the transportation sector—full development path.

The energy mix of Singapore's industrial sector is not expected to shift significantly by 2030, with a small proportion of oil-fired equipment used for heating to be converted to gas and electricity, and the share of oil in end consumption falling to 57.3%, gas rising to 15.9%, electricity rising to 25%, and coal remaining at 1.8%. Under the full development path, considering the cost and technical factors, oil-fired equipment will be

converted to hydrogen combustion or electrification respectively according to their respective characteristics, and coal equipment will be completely eliminated. By 2050, the share of oil in end consumption decreases to 39.5%, natural gas is 15.8%, and electricity rises to 44.7%, as shown in **Figure 7**.

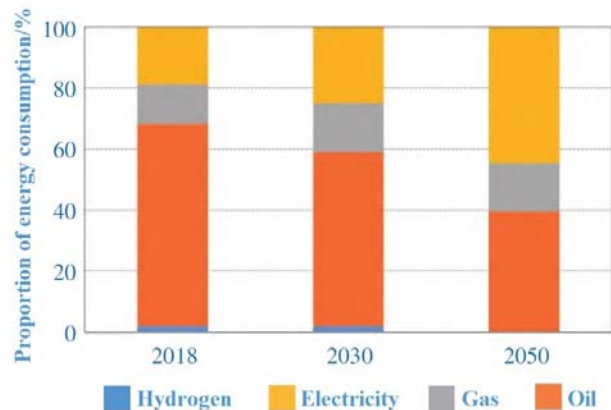


Figure 7. Changes in industrial sector energy consumption—full development path.

The structure of Singapore's energy consumption in 2050 under the full development path is shown in **Figure 8**, with electricity consumption of 9,219.9 kt standard oil, natural gas consumption of 1,427.7 kt standard oil, and oil consumption of 4,536 kt standard oil. The power sector reduces carbon emissions by developing renewable energy sources and importing clean electricity, and the carbon emissions from the fully developed pathway are estimated to be about $3,140 \times 10^4$ t according to the carbon emission factors given by the IPCC for each type of energy source (see **Table 3**).

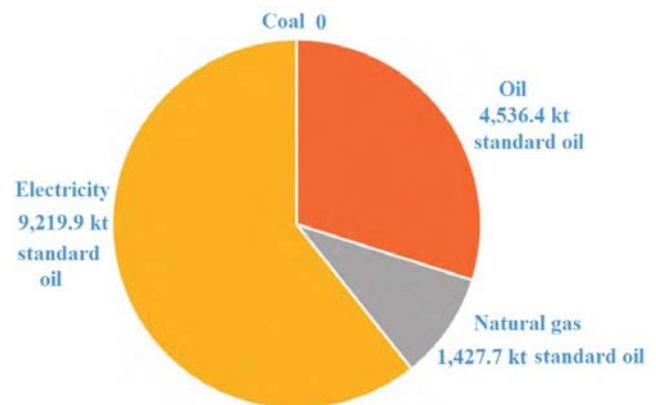


Figure 8. Energy consumption structure of Singapore in 2050—full Development path.

Table 3. Carbon emission factors of various types of energy consumption

Types of energy consumption	CO ₂ emission factors
Coal	94,600 kg/TJ
Oil	71,900 kg/TJ
Natural gas	56,100 kg/TJ
Electricity	0.4 kg/(kW·h)

4.2.2 Power supply mode

According to the terminal energy demand, the power demand of Singapore in 2030 is 711×10^8 kW·h and maximum load is 981×10^4 kW; the power demand in 2050 is $1,100 \times 10^8$ kW·h and maximum load is $1,500 \times 10^4$ kW. In 2050, the total installed capacity was $1,850 \times 10^4$ kW, among which solar energy resources were basically developed, and the installed capacity reached 900×10^4 kW, installed capacity of gas power and biomass reached 900×10^4 kW, and 50×10^4 kW respectively, as shown in **Figure 9**.

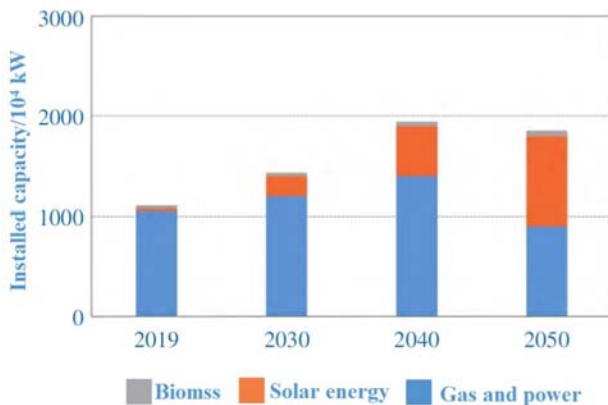


Figure 9. Installation structure changes—full development path.

According to the power balance analysis, due to the decrease of solar energy output at 7:00 pm, 900×10^4 kW of gas power installed capacity and 50×10^4 kW of biomass installed capacity cannot meet the power demand of about $1,500 \times 10^4$ kW. Considering the standby, about 850×10^4 kW of electricity should be added internationally. Transnational power transactions exceed 50% of the maximum load.

Combined with Singapore's geographical location, the power industry is diversified, importing 300×10^4 kW of electricity from Malaysia and Indonesia and 250×10^4 kW of electricity from Australia.

4.3 Economic development scenario of solar energy

4.3.1 Mode of energy transformation

Transportation department and the prediction method is consistent with the full development path. It is expected that electric vehicles in Singapore will account for 30% in 2030, with a total of more than 200,000 vehicles, and the new electricity demand of 68×10^8 kW·h. The electrification rate of the transportation sector has increased from 11% in 2018 to 36% in 2030. In 2050, the proportion of electric vehicles in Singapore will reach 48%, with more than 300,000 vehicles, the new electricity demand will increase by 100×10^8 kW·h compared with 2030, and the electrification rate of the transportation sector will increase to 48.5%, as shown in **Figure 10**.

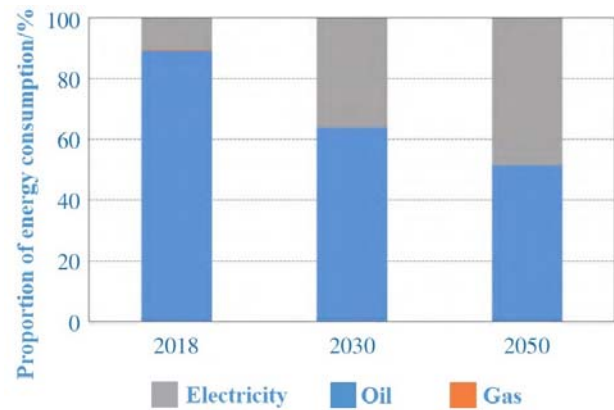


Figure 10. Changes in energy consumption of transportation sector—economic development path.

In the industrial sector, only considering using electricity to replace oil, the electrification rate in the industrial sector is expected to rise to 27% from 19% in 2018 by 2030. In 2050, with a pilot hydrogen replacement of new natural gas consumption, electrification in the industrial sector slowly grew to 30%.

Under the economic development path, the energy consumption structure of Singapore in 2050 is shown in **Figure 11**. Among them, electricity consumption 6,939.9 kt oil equivalent, natural gas consumption 1,727.7 kt oil equivalent, oil consumption 6,516 kt oil equivalent and coal consumption 130 kt oil equivalent. According to the IPCC carbon emission factor, the carbon emission of the economic development path is about $4,100 \times 10^4$ t.

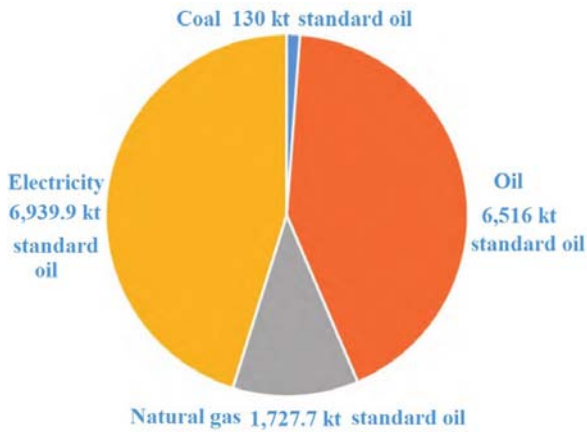


Figure 11. Energy consumption structure of Singapore by 2050—economic development path.

4.3.2 Power supply mode

According to the terminal energy demand, the power demand of Singapore in 2030 is 711×10^8 kW·h, the maximum load is 981×10^4 kW; the power demand in 2050 is 820×10^8 kW·h, and the maximum load is $1,300 \times 10^4$ kW. Under the economic development path, the installed solar energy capacity in 2030 will reach 200×10^4 kW, achieving the planning target. In 2040, with the economic development of infrastructure photovoltaics and inland floating photovoltaics, the installed solar capacity will increase by 360×10^4 kW; in 2050, all of Singapore's economical solar energy resources will be basically developed, with an installed capacity of about 600×10^4 kW, as shown in **Figure 12**.

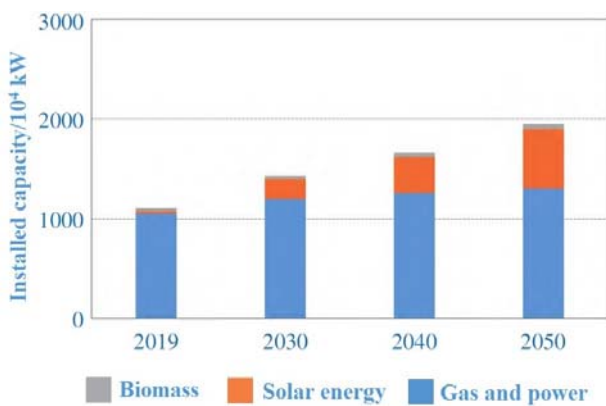


Figure 12. Changes in installed capacity structure—economic development path.

5. Conclusion

(1) According to the evaluation, in 2050, Singapore photovoltaic exploitable potential is about 968×10^4 kW, including rooftop photovoltaic

about 330×10^4 kW, building surface photovoltaic about 246×10^4 kW, land-based photovoltaic about 150×10^4 kW, floating photovoltaic about $138, 104$ kW, infrastructure photovoltaic about 104×10^4 kW, distributed solar accounted for about 74%. By 2050, roof, building and infrastructure PV will mainly be distributed development with high kWh cost, roof PV 0.09 ~ 0.12 SGD/(kW·h), building surface PV 0.10 ~ 0.12 SGD/(kW·h) and infrastructure PV 0.072 SGD/(kW·h). Land-based and floating photovoltaic are mainly developed with low cost, namely 0.038 SGD/(kW·h) and 0.04 ~ 0.06 SGD/(kW·h) respectively.

(2) Solar energy is the only renewable resource in Singapore that can be developed on a large scale. Two development paths are proposed according to the development degree and cost change of solar energy resources. Under the full development path, the electrification level reaches 61%, 16% higher compared with the economic development path; the installed renewable energy capacity is 51%, 19 percentage points higher compared with the economic development path.

(3) Singapore is unlikely to become carbon neutral by only relying on its own renewable energy resources, and needs to increase the proportion of cross-border transmission. Singapore has scarce renewable resources, wind and water energy, and solar energy is abundant. However, the land area is small, and it is difficult to carry out the construction of large-scale solar energy bases. Neither of the two development paths of research and planning can achieve carbon neutrality. In 2050, Singapore's carbon emissions under the full development path were $3,140 \times 10^4$ t, and about $4,100 \times 10^4$ t under the economic development path. Singapore needs to develop solar energy, upgrade the transnational transmission scale, install carbon capture systems, reduce carbon emissions, and achieve carbon neutrality.

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Conflict of interest

The authors declared no conflict of interest.

References

1. Khew EE. Renewable energy and its relevance for Singapore in 2065. In: Quah E (editor). Singapore 2065: Leading insights on economy and environment from 50 Singapore icons and beyond. Singapore: World Scientific Publishing Co. Pte. Ltd.; 2015. p. 113–118.
2. Energy Market Authority. Singapore electricity market outlook (SEMO) 2018 [Internet]. Singapore: EMA; 2019. 3rd ed. Available from: <https://www.ema.gov.sg/cmsmedia/Singapore%20Electricity%20Market%20Outlook%202018%20Final.PDF>.
3. Karthikeya BR, Negi S, Srikanth N. Wind resource assessment for urban renewable energy application in Singapore. *Renewable Energy* 2016; 87: 403–414.
4. Amin ZM, Hawlader MNA. A review on solar assisted heat pump systems in Singapore. *Renewable and Sustainable Energy Reviews* 2013; 26: 286–293.
5. King S, Wettergren P. Feasibility study of renewable energy in Singapore. Stockholm: KTH Royal Institute of Technology; 2011.
6. Quek A, Ee A, Ng A, *et al.* Challenges in environmental sustainability of renewable energy options in Singapore. *Energy Policy* 2018; 122: 388–394.
7. He J. Renewable bioenergy development in Singapore and recent discoveries on biofuel generation. 2012 AIChE Annual Meeting; 2012 Oct 28–Nov 2; Pittsburgh, PA, USA. New York: American Institute of Chemical Engineers; 2012.
8. Solar Energy Research Institute of Singapore. Solar photovoltaic (PV) roadmap for Singapore [Internet]. Singapore: SERIS; 2020. Available from: <https://www.nccs.gov.sg/docs/default-source/default-document-library/solar-photovoltaic-roadmap-for-singapore-a-summary.pdf>.
9. Dong Z, Yang D, Reindl T, *et al.* Satellite image analysis and a hybrid ESSS/ANN model to forecast solar irradiance in the tropics. *Energy Conversion and Management* 2014; 79: 66–73.
10. Ng H. Tender called for 3rd phase of railway noise barrier works [Internet]. Available from: <https://www.straitstimes.com/singapore/tender-called-for-3rd-phase-of-railway-noise-barrier-works>.
11. Zumbo L, Lerat JF, Connelli C, *et al.* Influence of defects on silicon heterojunction solar cell efficiency: Physical model and comparison with data. *AIP Advance* 2021; 11(1): 015044.
12. Gandhi O, Rodríguez-Gallegos CD, Gorla NBY, *et al.* Reactive power cost from PV inverters considering inverter lifetime assessment. *IEEE Transactions on Sustainable Energy* 2018; 10(2): 738–747.
13. Singapore National Environment Agency. E² Singapore [Internet]. Singapore: NEA; 2010. Available from: <http://www.e2singapore.gov.sg/DATA/0/docs/Booklet/E2S%20Publication.pdf>
14. Kokate A, Wagh M. Experimental analysis of performance ratio of solar rooftop photovoltaic system (SRTPV) for various roof orientation and tilt. *Journal of Physics: Conference Series* 2019; 1172(1): 012067.
15. Oh S, Seshadri R, Azevedo CL, *et al.* Accessing the impacts of automated mobility-on-demand through agent-based simulation: A study of Singapore. *Transportation Research Part A: Policy and Practice* 2020; 138: 367–388.
16. Li MZF, Lau DCB, Seah DWM. Car ownership and urban transport demand in Singapore. *International Journal of Transport Economics* 2011; 38(1): 47–70.
17. Fwa TF. 50 Years of transportation in Singapore: Achievements and challenges. Singapore: World Scientific Publishing Co. Pte. Ltd.; 2016. p. 1–576.