Contents list available at IJRED website
Int. Journal of Renewable Energy Development (IJRED)
Journal homepage: https://ijred.undip.ac.id

Research Article

Impacts of Solar Electricity Generation on the Thai Electricity Industry

Buncha Wattana[a]* and Phinyo Aungyut[b]

[a]Solar Energy and Energy Resources Research Unit, Faculty of Engineering, Mahasarakham University, Kantarawichai, Mahasarakham, 44150, Thailand

[b]Faculty of Engineering, Mahasarakham University, Kantarawichai, Mahasarakham, 44150, Thailand

Abstract. This paper analyses the impacts of electricity generation from solar energy on the Thai electricity industry. In this paper, three scenarios (REF, Solar2015 and Solar2018) are developed to represent an increased levels of electricity produced from solar energy. A Low Emissions Analysis Platform (LEAP) model is employed, in this paper, to assess the impacts for the period 2019–2037.This paper assesses and analyses the scenario impacts in terms of diversification of electricity generation, fossil fuel requirement and emissions of CO_2 and SO_2. The analysis reveals that increased electricity generation from solar energy would help diversify energy supply for electricity generation, reduce fossil fuel imports, and therefore help improve energy security of the country. Furthermore, it would help mitigating CO_2 and SO_2 emissions – an issue of environmental significance. Despite several benefits, there are a number of emerging barriers for promoting electricity generation from solar energy in Thailand. These include the intermittency of solar energy, high-capital cost, unsupportable grid infrastructure and unfavourable regulatory framework. This paper, therefore, suggests that the implementation of energy storage system, provision of financial incentives to potential investors, improvement of grid flexibility and the revision of the regulations to support solar energy business could be effective strategies in order to address the barriers facing the Thai electricity industry.

Keywords: Solar electricity generation, electricity industry, energy, environment and Thailand.

Article History: Received: 30th Aug 2021; Revised: 15th Oct 2021; Accepted: 26th Oct 2021; Available online: 3rd Nov 2021
How to Cite This Article: Wattana, B. and Aungyut, P. (2022) Impacts of Solar Electricity Generation on the Thai Electricity Industry. *International Journal of Renewable Energy Development*, 11(1), 157-163
https://doi.org/10.14710/ijred.2022.41059

1. Introduction

Electricity is one of the most important factors driving the development of the industrial, commercial and residential sectors. Especially Thailand, a country that has continued economic and social development which is widely distributed to all parts of the country in response to the government's policies. Accordingly, a demand for electricity has consistently increased and is expected to grow continuously. Over the period 2010–2020, electricity consumption in Thailand increased by 25%, from 149,301 GWh in 2010, to 187,046 GWh in 2020 (EPPO 2021a). In order to meet the growing demand for electricity, Thailand has been highly dependent on fossil fuels for power production, especially natural gas – accounting for more than 60% of fuel consumption for producing electricity in 2019 (DEDE 2019a). Due to limited energy resources, a substantial amount of energy has been imported for electricity generation. In order to reduce dependency on energy import and to diversify the energy sources used for generating electricity, the government has a policy to promote the use of renewable energy for power production. Renewable energy, particularly solar energy, appears to be an attractive option for the government because solar energy is clean and abundant renewable energy source available. More importantly, Thailand has great solar potential. The average annual solar energy is relatively high as compared with several countries, with most parts of the country exposed to the highest solar radiation between April and May in the range 20–23 MJ/m^2/day (DEDE 2014). A number of studies have been conducted on the impacts of solar electricity generation in the case of Thailand. Much of the studies have mainly focused on technical aspect including Greacen and Green 2001, Adhikari *et al.* 2003, Sakulpong *et al.* 2011, Kengpol *et al.* 2012, Thawonngamyingsakul and Kiatsiriroat 2012, Iemsomboon *et al.* 2013, Mansiri *et al.* 2014, Kohsri *et al.* 2018, Sonsaree *et al.* 2018, Yoomak *et al.* 2019, Fachrizal and Tang 2019, Manosukritkul *et al.* 2019, Imjai *et al.* 2020 and Narkwatchara *et al.* 2021. In addition, some research works has been specifically focused on the Thai electricity grid impacts in terms of system reliability, for example, Siritiprussamee *et al.* 2019, Bhasaputra *et al.* 2015, Sansilah *et al.* 2015, Boonmee *et al.* 2009 and Chokmaviroj *et al.* 2006. Several studies have assessed the environmental impacts of solar energy, for example, Tanavanit *et al.* 2004, Limmeechokchai and

* Corresponding author: buncha.w@msu.ac.th

Suksoontornsiri 2007, Kittner *et al*. 2013, Khaenson *et al*. 2016, Khaenson *et al*. 2017, Eskew *et al*. 2018, Faircloth *et al*. 2019. Some studies have provided an economic analysis of solar energy, for instance, Tongsopit *et al*. 2019, Chaianong *et al*. 2020 and Arif *et al*. 2021. Despite numerous prior research works on solar energy, new research works would be needed due to policy changes as a result of rapid technological advancement of solar energy. In 2015, the government has implemented the Alternative Energy Development Plan (AEDP2015) for the period 2015–2036 (DEDE 2015). This plan aims to increase the proportion of renewable energy, from 9,025 KTOE in 2014 to 39,402 KTOE in 2036 or 30.1% of total energy consumption. The solar generating capacity is expected to grow to 6,000 MW in 2036. Due to a rapid technological advancement, the government has developed, in 2018, the new Alternative Energy Development Plan (AEDP2018) for the period 2018–2037 (DEDE 2018). Under this new plan, the proportion of electricity from solar production would rise to 20% in 2037 – more than three-fold increase in comparison to 2018. The solar generating capacity is estimated to increase considerably to 15,574 MW in 2037. With a view to provide recommendations in response to the government's policy changes, this paper, therefore, aims to analyze the impacts of an increase in solar electricity generation on the Thai electricity industry in terms of diversification of electricity generation, generation technology mix, primary energy mix and emissions of CO_2 and SO_2.

2. Methodology

To assess the impacts of solar electricity generation, the Low Emissions Analysis Platform (LEAP) was selected. LEAP is a widely-used software tool for energy policy, climate change mitigation and air pollution abatement planning developed by the Stockholm Environment Institute (SEI) (SEI 2020). LEAP has been adopted by thousands of organizations in more than 190 countries worldwide. Its users include government agencies, academics, non-governmental organizations, consulting companies, and energy utilities, and it has been used at scales ranging from cities and states to national, regional and global applications. LEAP has been employed by numerous studies to assess the energy and environmental impacts of renewable energy (Kusumadewi *et al.* 2019, Hu *et al.* 2019, Rivera *et al.* 2019, Mirjat *et al.* 2018, Wang *et al.* 2018, Kresnawan *et al.* 2018, Emodi *et al.* 2017, Bhuvanesh *et al.* 2017, Shahinzadeh *et al.* 2016, McPherson and Karney 2014, Park *et al.* 2013, Afreen *et al.* 2013 and Lin *et al.* 2010).

In this paper, the development of scenario was mainly based on the Power Development Plan (PDP) and the Alternative Energy Development Plan (AEDP). The scenario analysis covered for the time period of 2019–2037. In this study, scenario development was mainly focused on solar electricity generation. For this purpose, this paper developed two alternative scenarios, namely, the Solar2015 and Solar2018 scenarios. In addition to the two alternative scenarios, this paper included a REF scenario which represent a continuation of current trends in primary energy and technology mix for power generation. The two alternative scenarios (Solar2015 and Solar2018 scenarios) were primarily intended to increase shares of solar energy in electricity generation. In the Solar2015 scenario, the generating capacity of solar energy would increase to 6,000 MW in 2037. The solar2018 scenario was developed to represent greater role of solar energy in power production. The installed capacity of solar energy, under the solar2018 scenario, is expected to grow to 15,574 MW in 2037. Table 1 provides the details of key features of the three scenarios.

3. Data Considerations

The data required by this study include electricity consumption, power generation by fuel types, installed capacities by generating technologies, electricity losses, efficiencies of power plant technologies, electricity load curve and electricity demand growth. The electricity consumption data, power generation by fuel types, installed capacities and electricity losses are available from Energy Balance report and Alternative Energy Situation report, published by the Department of Alternative Energy Development and Efficiency (DEDE) (DEDE 2019a and DEDE 2019c). The information on the electricity demand growth can be achieved from the Power Development Plan: First Revision (PDP2018rev1) developed by the Energy Policy and Planning Office (EPPO), Ministry of Energy (EPPO 2020). The shares of installed capacity by each plant type (e.g., steam turbine, combine-cycle, co-generation, gas turbine, hydro, solar, wind, biomass, biogas, municipal solid waste and geothermal) can be taken from the PDP2018rev1 (EPPO 2020). The information on the efficiencies of power plant technologies can be taken from external sources including International Energy Agency (IEA) and relevant literature (IEA 2013 and Sorapipatana 2013). The data on electricity load curve was obtained from the Electricity Generating Authority of Thailand (EGAT) and the relevant literature (EGAT 2020 and Siritiprussamee *et al.* 2014).

Table 1
Key features of three scenarios

Scenario	Scenario features
REF scenario	• Continue with current primary energy and technology mix for electricity generation. • The share of solar energy in electricity production would be 5% until the year 2037. • The generating capacity of solar energy is expected to grow to 4,517 MW in 2037.[a]
Solar2015 scenario	• Slight increase of solar electricity installed capacity to 6,000 MW in 2037.[b]
Solar2018 scenario	• Greater role of solar in electricity production, thus resulting in a considerable increase of solar electricity installed capacity to 15,574 MW in 2037.[b]

Note: [a] Information on the generating capacity of current situation is from Thailand Alternative Energy Situation report.
[b] The generating capacity of solar energy in the case of Solar2015 and Solar2018 scenarios is from the AEDP2015 and AEDP2018 respectively.
Sources: DEDE (2015) DEDE (2018) DEDE (2019c)

4. Empirical Results and Discussions

This paper assesses the impacts of solar electricity generation on the Thai electricity industry in terms of diversification of electricity generation, fossil fuel consumption, CO_2 emissions and SO_2 emissions for the period 2019-2037.

4.1. Diversification of electricity generation

Figure 1 shows that electricity production under the REF, Solar2015 and Solar2018 scenarios would increase from 206 TWh in 2019, to 340 TWh in 2037. Over the entire studied period, the electricity produced from natural gas under the REF, Solar2015 and Solar2018 scenarios would increase, from 126 TWh, to 209 TWh, 203 TWh and 184 TWh respectively. Over the period 2019–2037, the generation of electricity from coal and lignite under the REF, Solar2015 and Solar2018 scenarios would increase, from 37 TWh, to 60 TWh, 56 TWh and 49 TWh respectively. A drop in electricity generated from natural gas, and coal and lignite under the Solar2015 and Solar2018 scenarios in comparison with the REF scenario would be mainly from an increase in solar electricity generation. This could help diversify energy supply for power production and hence help enhance energy security of the country. It is further noticed from Figure 1 that electricity generation from solar energy would increase considerably. Electricity generated from solar energy in 2037 is expected to rise by 1.6 times in the REF scenario, 2.2 times in the Solar2015 scenario, and 5.8 times in the Solar2018 scenario as compared to 2019. Electricity produced from Solar in 2037 is expected to grow to 10 TWh in the Solar2015 scenario and 26 TWh in the Solar2018 scenario – more than double increase as compared to 2019.

In view of electricity generation share by fuel type, the percentage share of natural gas in total electricity generation in the case of Solar2015 and Solar2018 scenarios in 2037 would decrease by 2% and 7%, respectively, as compared with the share in the year 2019 when natural gas accounted for 61% of total power production (as shown in Table 2).

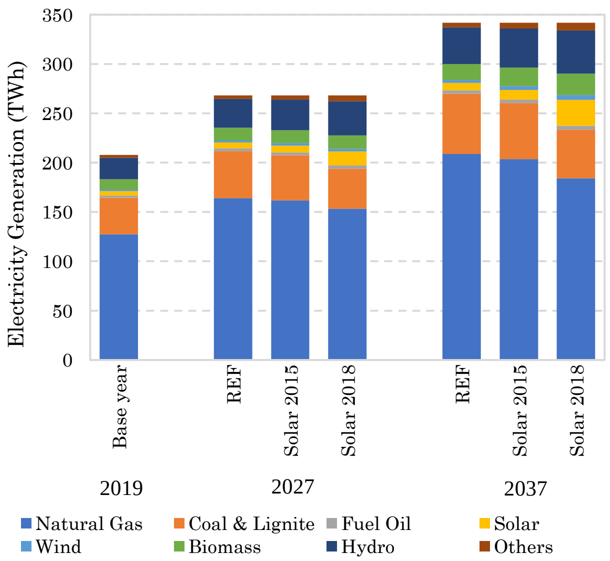


Fig. 1 Electricity generation by fuel type for the period 2019–2037

Table 2
Electricity generation share by fuel type for all three scenarios

Fuel type	2019	2037		
	Base Year	REF	Solar2015	Solar2018
Natural gas	61%	61%	59%	54%
Coal & Lignite	18%	18%	17%	14%
Fuel oil	1%	1%	1%	1%
Solar	2%	2%	3%	8%
Wind	1%	1%	1%	2%
Biomass	5%	5%	5%	6%
Hydro	11%	11%	12%	13%
Others	1%	1%	2%	2%

Notes: Others include biogas and waste-to -energy

This decrease would be contributed by the government's policy to diversify primary energy supply for electricity generation. This is due to the fact that electricity production in Thailand has been mainly dependent on natural gas over the last three decades (EPPO 2021b). According to PDP2018rev1 (DEDE 2020), the Thai government has a policy to enhance the energy security by reducing the share of natural gas in electricity production and substituting by renewable energy. Moreover, the share of coal and lignite would also decrease to 17% in the Solar2015 scenario and 15% in the Solar2018 scenario. These decreases would be substituted by an increased share of renewable energy including solar, biomass, wind and hydro in power production. Especially, the share of solar energy in power production under the Solar2018 scenario is expected to grow considerably from 2% in 2019, to 8% in 2037.

4.2. Fossil fuel consumption

This paper employs fossil fuels consumption as an indicator to assess a decline in fossil fuel consumption attributed to an increased electricity generation from solar. Table 3 shows the fossil fuels consumption for power generation in the case of the REF, Solar2015, and Solar2018 scenarios. And, Figure 2 provides changes in fossil fuel consumption by fuel type in 2037 for the Solar2015 and Solar2018 scenarios in comparison with the REF scenario.

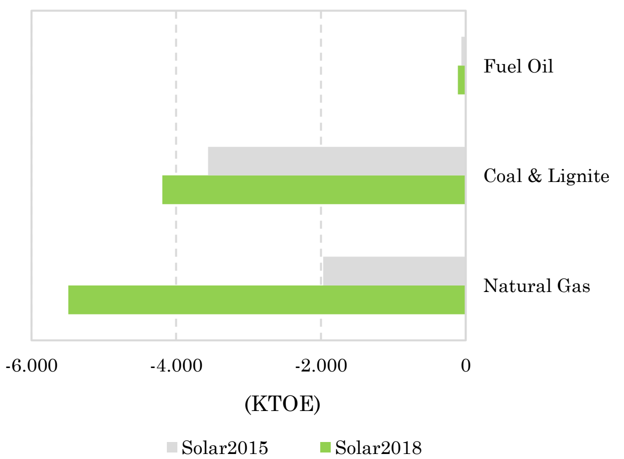
It can be seen from Table 3 that over the period 2019-2037, fossil fuel consumption in the case of REF scenario increased considerably, from 33,143 KTOE in 2019, to 55,996 KTOE in 2037. In 2037, fossil fuel consumption under the Solar2015 and Solar2018 scenarios would be 9.9% and 17.5%, respectively, lower than in the case of the REF scenario. The fossil fuel inputs for electricity generation under the Solar2015 scenario is expected to grow to 50,408 KTOE in 2037 – a decrease of 5,588 KTOE in comparison with the REF scenario. In the Solar2018 scenario, fossil fuel consumption in 2037 is expected to be 46,204 KTOE – a reduction of 9,792 KTOE in fossil consumption for power production as compared with the REF scenario. Such a reduction is a consequence of increased share of renewable energy especially solar in electricity generation.

It is further shown from Figure 2 that major contribution to a decline in fossil fuels consumption for electricity generation in the case of Solar2015 and Solar2018 scenarios would be from natural gas and coal and lignite. The decline in the demand for both natural gas and coal and lignite would help reduce fossil fuels imports for electricity generation. This is because natural gas and coal imports have been consistently increasing since 2000 (EPPO 2021c and EPPO 2021d). In addition, natural gas imports accounted for 30% of total natural gas supply in 2019 and more than 75% of total natural gas consumption of the country has been employed as fuel inputs for power production (DEDE 2019a). For coal and lignite, coal consumption for power generation accounted for more than 30% of total coal imports in 2019 (DEDE 2019a). An increased electricity generation from solar energy would, therefore, help reduce fossil fuel imports and hence help improve security of energy supply – major energy policy of the country.

Table 3
Fossil fuels consumption for electricity generation

Year	REF Scenario (KTOE)	Solar2015 Scenario (%)	Solar2018 Scenario (%)
2019	33,143	-	-
2027	43,166	(-5.1)	(-9.2)
2037	55,996	(-9.9)	(-17.5)

Notes: Number in brackets shows percentage changes from the REF scenario.



Note: This figure presents the changes in fossil fuels consumption for electricity generation in the Solar2015 and Solar2018 scenarios in the year 2037 as compared with the REF scenario.

Fig. 2 Changes in fossil fuel consumptions by fuel types in 2037

4.3. CO_2 emissions

In view of CO_2 emissions, Table 4 shows that CO_2 emissions under the REF scenario is estimated to increase from 92 million tonnes in 2019, to 150 million tonnes in 2037, an increase of 58 million tonnes over the 2019 emission level. In the case of Solar2015 and Solar2018 scenarios, CO_2 emissions in 2037 would be, respectively, 9.4 million tonnes (6.3%) and 24.8 million tonnes (16.6%) lower than the emissions in the REF scenario. It is further observed that the Solar2018 scenario would result in highest CO_2 savings – 24.8 million tonnes in 2037, as compared with the REF scenarios. A reduction in CO_2 emissions is a result of a decrease in fossil fuels consumption for power generation. Therefore, it appears that higher shares of renewable energy would result in higher reduction in fossil fuels inputs for electricity generation and hence lower CO_2 emissions.

4.4. SO_2 emissions

In conformity with CO_2 emissions, SO_2 emissions, under the REF scenario, would increase from 351 thousand tonnes in 2019, to 573 thousand tonnes in 2037, an increase of 222 thousand tonnes over the 2019 emission level (as shown in Table 5). It is further shown from Table 5 that SO_2 emissions in the case of Solar2015 and Solar2018 scenarios in 2037 would be, respectively, 133 thousand tonnes (23.2%) and 158 thousand tonnes (27.5%) lower than the emissions in the REF scenario. A decline in SO_2 emissions would be mainly from a decrease in coal and lignite consumption for power generation. It is widely known that coal and lignite are major contributor to SO_2 emission and importantly, causes acid rain which has apparently been a serious environmental problem for Thailand over the last three decades or so.

Table 4
CO_2 emissions from electricity production over the period 2019–2037

Year	REF Scenario (million tonnes)	Solar2015 Scenario (million tonnes)	Solar2018 Scenario (million tonnes)
2019	92	-	-
2027	118	(-3.81)	(-10.10)
2037	150	(-9.40)	(-24.82)

Notes: Number in brackets shows CO_2 emission changes from the REF scenario.

Table 5
SO_2 emissions from electricity production over the period 2019–2037

Year	REF Scenario (thousand tonnes)	Solar2015 Scenario (thousand tonnes)	Solar2015 Scenario (thousand tonnes)
2019	351	-	-
2027	450	(-53.2)	(-63.0)
2037	573	(-133.3)	(-157.8)

Notes: Number in brackets shows SO_2 emission changes from the REF scenario.

5. Policy implications

The impacts of increased electricity generation from solar energy are analyzed in this paper with a view to provide strategies in order to address emerging barriers for promoting solar based electricity generation in Thailand. The foregoing results suggests that greater role of solar energy in the electricity generation would help diversifying primary energy supply for power generation. Moreover, it would contribute to a reduction in fossil fuels consumption for electricity generation and hence result in a decrease in fossil fuel imports. An improvement in the diversification of primary energy supply supplemented by a decline in fossil fuels imports would, therefore, help enhance the energy security of the country. Furthermore, increased electricity generation from solar energy would have a positive impact on the environment. As previously discussed, increased contribution of solar energy to electricity generation would considerably reduce the use of fossil fuels for electricity generation and, therefore, help mitigating CO_2 and SO_2 emissions. The attractiveness of solar energy would considerably enhance when considering in the context of Thailand – country that has great solar potential.

Despite the fact that solar energy would provide several benefits to the Thai society, the promotion of solar energy could face numerous barriers including the intermittency of solar energy, capital-intensive investment, unsupportable grid infrastructure, traditional regulatory framework. The intermittency of solar energy would make it inefficient and unreliable for supplying electricity to the system. Intermittency appears to be one of the major weaknesses of solar energy. The electricity from solar is generated only when the sun is shining which is mostly less than 6 hours per day. In addition to daily fluctuations caused by sunshine duration, variability caused by clouds could make it more difficult for the grid operator to predict additional quantity needed during the next hour of each day. This intermittent nature of solar energy would disrupt the conventional methods for planning the daily operation of the electricity grid. The implementation of energy storage system appears to be one strategy to address the issues of the intermittency of solar energy. The energy storage system would allow the solar electricity generation to be stored for use on demand especially during the night time. However, high price of battery has been one major obstacles for the deployment of energy storage system in renewable-based electricity in the last two decades. The emerging innovative advancement in battery due to disruptive technology transitions would lead to lower battery price in the near future. This would help integrate solar into the electricity grid more effectively.

Another barrier would be capital-intensive investment for solar energy. Its high initial capital cost but inefficient and unreliable nature would make solar energy get a low rate of return on investment. As a result, solar energy project itself will not be able to attract investor interest. In order to make solar project more attractive, the Thai government should initially provide financial incentives through investment subsidy and soft loans provision to potential investors until cost of solar project investment decline.

Unsupportable grid infrastructure would emerge as one major barrier. This is because the current structure of the Thai electricity sector is in the form of centralized electricity system which is not designed to support distributed generation characterizing by small–scale and intermittent generators like solar energy. A high penetration of solar-based electricity generation in the power grid could cause difficulties in the system operation, and management, for example voltage instability, harmonics, phase unbalance, voltage drop, and power quality degradation. Some studies have provided useful analysis on the protection of the electricity industry, for example, Abd el-Ghany *et al.* 2019, Adly *et al.* 2020. Additional system flexibility would be needed in order to transform the traditional electricity grid towards the new modern grid that effectively integrate solar energy into the system. Such flexibilities include, for example, supply-side flexibility, demand-side flexibility, well-developed grid infrastructure, and improved system operations.

The issue of regulatory framework would be also important. The regulatory arrangements for the Thai electricity industry for the last sixty years have been primarily designed to support centralized electricity system. The traditional regulatory framework would, therefore, hinder the penetrations of solar energy in electricity system. New rules and regulation are essentially required in order to make the electricity system fit for decentralized generation like solar energy.

6. Conclusion

This paper analyses the impacts of solar electricity generation on the Thai electricity industry in terms of diversification of electricity generation, fossil fuel consumption, CO_2 emissions and SO_2 emissions for the period 2019-2037. The analyses reveal that greater role of solar energy in the electricity generation would have positive impacts on the Thai electricity generation from several aspects including improving the diversification of primary energy supply for electricity generation, reducing fossil fuel consumptions for power production, less reliance on fossil fuel sources and environmentally friendly electricity generation. Despite several benefits, the promotion of solar energy could face numerous barriers including the intermittency of solar energy, high-capital cost, unsupportable grid infrastructure and unfavorable regulatory framework. This paper, therefore, recommends that implementation of energy storage system, provision of financial incentives to potential investors, improvement of grid flexibility and the revision of the regulations to support solar energy business could be effective strategies in order to address the barriers facing the Thai electricity industry.

Acknowledgments

This research was financially supported by Faculty of Engineering, Mahasarakham University (Grant year 2020). The authors wish to extend appreciation to the Solar Energy and Energy Resources Research Unit, Faculty of Engineering, Mahasarakham University for providing research facilities.

References

Abd el-Ghany, H. A., Elsadd, M. A., & Ahmed, E. S. (2019). A faulted side identification scheme-based integrated distance protection for series-compensated transmission lines. International Journal of Electrical Power and Energy Systems, 113(June), 664–673. https://doi.org/10.1016/j.ijepes.2019.06.021.

Adhikari, S., Kumar, S. and Siripuekpong, P. (2003). Performance of Household Grid-Connected PV System in Thailand, Progress in Photovoltaics: *Research and Applications*, 11, 557-564.

Adly, A. R., Ali, Z. M., Elsadd, M. A., Abdel Mageed, H. M., & Abdel Aleem, S. H. E. (2020). An integrated scheme for a directional relay in the presence of a series-compensated line. International Journal of Electrical Power and Energy Systems, 120(March), 106024. https://doi.org/10.1016/j.ijepes.2020.106024.

Afreen, S. and James L. Wescoat Jr (2013). Energy use in large-scale irrigated agriculture in the Punjab province of Pakistan *Water International*, 38(5), 571-586. https://doi: 10.1080/02508060.2013.828671.

Arif, S., Taweekun, J., Ali, H. M., Yanjun, D. A. I., & Ahmed, A. (2021). Feasibility study and economic analysis of grid connected solar powered net zero energy building (NZEB) of shopping mall for two different climates of Pakistan and Thailand. Case Studies in Thermal Engineering, 26(April), 101049. https://doi.org/10.1016/j.csite.2021.101049.

Bhasaputra, P., Sansilah, C., & Pattaraprakorn, W. (2015). Impact of solar and wind power development plan in Thailand by considering frequency response of power system. ECTI-CON 2015 - 2015 12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology. https://doi.org/10.1109/ECTICon.2015.7207000.

Bhuvanesh, A., Christa, S. T. J. and Kannan, S. (2017). Least Cost Electricity Generation Planning for China with Low GHG Emission Using LEAP and EnergyPLAN. *2017 IEEE International Conference on Computational Intelligence and Computing Research,* ICCIC 2017, 8524458.

Boonmee, C., Plangklang, B. and Watjanatepin, N. (2009). System performance of a three-phase PV-grid-connected system installed in Thailand: Data monitored analysis. Renewable Energy, 34(2), 384–389. https://doi.org/10.1016/j.renene.2008.05.022.

Chaianong, A., Bangviwat, A., Menke, C., Breitschopf, B., & Eichhammer, W. (2020). Customer economics of residential PV–battery systems in Thailand. Renewable Energy, 146, 297–308. https://doi.org/10.1016/j.renene.2019.06.159.

Chokmaviroj, S., Rakwichian, W. and Yammen, S. (2006). Performance of a 500 kWP grid connected photovoltaic system at Mae Hong Son Province, Thailand. Renewable Energy, 31(1), 19–28. https://doi.org/10.1016/j.renene.2005.03.004.

DEDE (2014). *Handbook for the Development and Investment in Renewable Energy Series 2 Solar Energy*. Department of Alternative Energy Development and Efficiency, Ministry of Energy, Bangkok, Thailand.

DEDE (2015). *Alternative Energy Development Plan (AEDP2015)* Department of Alternative Energy Development and Efficiency, Ministry of Energy, Bangkok, Thailand.

DEDE (2018). *Alternative Energy Development Plan (AEDP2018)* Department of Alternative Energy Development and Efficiency, Ministry of Energy, Bangkok, Thailand.

DEDE (2019a). *Energy balance of Thailand 2019. Department of Alternative Energy Development and Efficiency*, Ministry of Energy, Bangkok, Thailand. https://www.dede.go.th/download/stat63/Energy_Balance_of_Thailand_2562_for_web.pdf. Accessed on 14 September 2020.

DEDE (2019b). *Summary of the public hearing on the draft of the Alternative Energy Development Plan 2018 (AEDP2018).* Department of Alternative Energy Development and Efficiency, Ministry of Energy, Bangkok, Thailand.

DEDE (2019c). *Thailand alternative energy situation 2019.* Department of Alternative Energy Development and Efficiency, Ministry of Energy, Bangkok, Thailand. https://www.dede.go.th/download/stat63/Thailand%20Alternative%20Energy%20Situation%202019.pdf. Accessed on 14 September 2020.

EGAT (2020). *Electricity Peak Demand of National Grid. Electricity Generating Authority of Thailand*, Nonthaburi. https://www.egat.co.th/index.php?option=com_content&view=article&id=348&Itemid=116. Accessed on 14 September 2020.

EPPO (2020). *Power Development Plan First Revision (PDP2018 1st Revision).* Energy Planning and Policy Office, Bangkok, Thailand. http://www.eppo.go.th/images/Infromation_service/public_relations/PDP2018/PDP2018Rev1.pdf. Accessed on 20 December 2020.

EPPO (2021a). *Thailand electricity consumption for the whole country: 2002–2020,* Energy Planning and Policy Office, Bangkok, Thailand. http://www.eppo.go.th/index.php/th/energy-information/static-energy/static-electricity?orders[publishUp]=publishUp&issearch=1. Accessed on 14 January 2021.

EPPO (2021b). *Thailand electricity production classified by fuel type: 2002–2020*, Energy Planning and Policy Office, Bangkok, Thailand. http://www.eppo.go.th/index.php/th/energy-information/static-energy/static-electricity?orders[publishUp]=publishUp&issearch=1. Accessed on 14 January 2021.

EPPO (2021c). *Thailand natural gas imports: 1986–2019*, Energy Planning and Policy Office, Bangkok, Thailand. http://www.eppo.go.th/index.php/th/energy-information/static-energy/static-gas?orders[publishUp]=publishUp&issearch=1. Accessed on 14 January 2021.

EPPO (2021d). *Thailand coal imports: 1986–2020*, Energy Planning and Policy Office, Bangkok, Thailand. http://www.eppo.go.th/index.php/th/energy-information/static-energy/coal-lignite?orders[publishUp]=publishUp&issearch=1. Accessed on 14 January 2021.

Emodi, N., Emodi, C., Girish, G. P. and Emodi, A. (2017). Energy Policy for Low Carbon development in Nigeria: A LEAP Model Application, *Renewable and Sustainable Energy Reviews*, 68, 247-261.

Eskew, J., Ratledge, M., Wallace, M., Gheewala, S. H. and Rakkwamsuk, P. (2018). An environmental Life Cycle Assessment of rooftop solar in Bangkok, Thailand, Renewable Energy, 123, 781-792.

Fachrizal, M. and Tang, J. (2019). Forecasting annual solar PV capacity installation in Thailand residential sector: A user segmentation approach. Engineering Journal, 23(6), 99–115. https://doi.org/10.4186/ej.2019.23.6.99.

Faircloth, C. C., Wagner, K. H., Woodward, K. E., Rakkwamsuk, P. and Gheewala, S. H. (2019). The environmental and economic impacts of photovoltaic waste management in Thailand, Resources, Conservation and Recycling, 143, 260-272.

Greacen, C. and Green, D. (2001). The role of bypass diodes in the failure of solar battery charging stations in Thailand, Solar Energy Materials and Solar Cells, 70(2), 141-149.

Hu, G., Ma, X. and Ji, J. (2019). Scenarios and policies for sustainable urban energy development based on LEAP model – A case study of a postindustrial city: Shenzhen China, *Applied Energy*, 238, 876-886.

IEA (2013) *Southeast Asia energy outlook: World energy outlook special report*, International Energy Agency, Paris, France.

Iemsomboon, P., Pati, T. and Bhumkitipich, K. (2013). Performance Study of Micro Hydro Turbine and PV for Electricity Generator, Case Study: Bunnasopit School, Nan Province, Thailand, Energy Procedia, 34, 235-242.

Imjai, T., Thinsurat, K., Ditthakit, P., Wipulanusat, W., Setkit, M., & Garcia, R. (2020). Performance study of an integrated solar water supply system for isolated agricultural areas in Thailand: A case-study of the royal initiative project. Water (Switzerland), 12(9). https://doi.org/10.3390/w12092438.

Kengpol, A., Rontlaong, P. and Tuominen, M. (2012). Design of a Decision Support System for Site Selection Using Fuzzy AHP: A Case Study of Solar Power Plant in North Eastern Parts of Thailand. Proceedings of PICMET '12: Technology Management for Emerging Technologies, 734-743.

Khaenson, W., Maneewan, S. Punlek, C. Chindaraksa, S. and Rachapradit, N. (2016). Life Cycle Assessment of Power Generation from Solar Energy in Thailand, Environmental Science and Sustainable Development, 223-229.

Khaenson, W., Maneewan, S. and Punlek, C. (2017). Environmental Impact Analysis of Solar Power Generation Process Using Multicrystalline and Amorphous Silicon Solar Cells in Thailand, International Energy Journal, 17, 113-124.

Kittner, N., Gheewala, S. H. and Kamens, R. M. (2013). An environmental life cycle comparison of single-crystalline and amorphous-silicon thin-film photovoltaic systems in Thailand, Energy for Sustainable Development, 17(6), 605-614.

Kohsri, S., Meechai, A., Prapainainar, C., Narataruksa, P, Hunpinyo, P. and Sin, G. (2018). Design and preliminary operation of a hybrid syngas/solar PV/battery power system for off-grid applications: A case study in Thailand, Chemical Engineering Research and Design, 131, 346-361.

Kresnawan, M. R., Safitri, I. A. and Darmawan, I. (2018). *Long Term Projection of Electricity Generation Sector in East Kalimantan Province: LEAP Model Application*, in 12th South East Asian Technical University Consortium (SEATUC) Yogyakarta, Indonesia; https://doi: 10.1109/SEATUC.2018.8788875, 1-5.

Kusumadewi, T.V., Winyuchakrit, P., Misila, P. and Limmeechokchai, B. (2017). GHG Mitigation in Power Sector: Analyzes of Renewable Energy Potential for Thailand's NDC Roadmap in 2030, *Energy Procedia,* 138, 69-74.

Limmeechokchai, B. and Suksuntornsiri, P. (2007). Assessment of cleaner electricity generation Technologies for net CO2 mitigation in Thailand, *Renewable and Sustainable Energy Reviews*, 11(2), 315-330.

Lin, J., Cao, B., Cui, S., Wang, W. and Bai, X. (2010). Evaluating the effectiveness of urban energy conservation and GHG mitigation measures: The case of Xiamen city, *China Energy Policy*, 38, 5123-5132.

Manosukritkul, P., Titiroongruang, W., Niemchareon, S., Siriwongrungson, V., Kittisontirak, S. & Sriprapa, K. (2019). Prediction of the Power Generation Solar Power Plant System in Thailand. International Journal of Simulation: Systems, Science & Technology, I, 1–11. https://doi.org/10.5013/ijssst.a.20.03.18.

Mansiri, K., Sukchai, S. and Sirisamphanwong, C. (2014). Investigations to conduct a study about possibilities to use small scale solar dish Stirling engine system in Thailand. *Energy Procedia*, 56, 367-377.

McPherson, M. and Karney, B. (2014). Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector, *Energy Policy*, 68, 146-157.

Mirjat, N. H., Harijan, K. and Valasai, G. (2018). Long-Term Electricity Demand Forecast and Supply Side Scenarios for Pakistan (2015-2050): A LEAP Model Application for Policy Analysis, *Energy*, 163, 512-526.

Narkwatchara, P., Ratanatamskul, C., & Chandrachai, A. (2021). Performance analysis of electricity generation from grid-connected photovoltaic system using All-Sky Index for Smart City projects in Thailand. Renewable Energy, 171, 315–327. https://doi.org/10.1016/j.renene.2021.02.107.

Park, N., Yun, S. and Jeon, E. (2013). An analysis of long-term scenarios for the transition to renewable energy in the Korean electricity sector, *Energy Policy*, 52, 288-296.

Rivera-González, L., Bolonio, D., Mazadiego, L. F. and Valencia-Chapi, R. (2019). Long-Term Electricity Supply and Demand Forecast (2018-2040): A LEAP Model Application towards a Sustainable Power Generation System in Ecuador, *Sustainability*, 11(19), 5316; https://doi.org/10.3390/su11195316.

Sansilah, C., Bhasaputra, P. and Pattaraprakorn, W. (2015). Frequency response for next decade solar power development plan in Thailand part 2: A case study of PDP 2010 Version 3. GMSARN International Journal, 9(2), 67–72. http://gmsarnjournal.com/home/wp-content/uploads/2015/08/vol9no2.pdf#page=36.

SEI (2020). Low Emissions Analysis Platform (LEAP), Stockholm Environment Institute – U.S. Center, Somerville, MA.

Sakulpong, R., Pornsuwancharoen, N. and Yupapin, P. P. (2010). Potential of using a Solar-Electricity Hybrid System in North-East of Thailand. *Procedia Engineering*, 8, 67-74.

Shahinzadeh, H., Fathi, S. H. and Hasanalizadeh-Khosroshahi, A. (2016). Long-term energy planning in IRAN using LEAP scenario: Using combined heat and power (CHP). *2016 Iranian Conference on Renewable Energy & Distributed Generation (ICREDG)*, Mashhad; https://doi: 10.1109/ICREDG.2016.7875915, 32-37.

Siritiprussamee, P., Bhanthumnavin, V. and Chansa-ngavej, C. (2019). Power security and reliability impact management: Case study of Thailand. Journal of Social Development, 13(2), 57–87.

Siritiprussamee, P., Suwannarat, W. and Dulyarittirong, R. (2014). Analysis of Thailand Electricity Demand Pattern, *Journal of Environmental Management,* 10(1), 1–18. (In Thai)

Sonsaree, S., Asaoka, T., Jiajitsawat, S., Aguirre, H. and Tanaka, K. (2018). A small-scale solar Organic Rankine Cycle power plant in Thailand: Three types of non-concentrating solar collectors. *Solar Energy*, 162, 541-560.

Sorapipatana, C. (2013). An Assessment of Energy Security in Thailand's Power Generation. Final Report submitted to the National Science and Technology Development Agency (NSTDA). (In Thai).

Suksuntornsiri, P. and Limmeechokchai, B. (2007). Assessment of cleaner electricity generation technologies for net CO_2 mitigation in Thailand. *Renewable and Sustainable Energy Reviews*, 11(2), 315-330.

Tanatvanit, S., Limmeechokchai, B. and Shrestha, R. M., (2004). CO2 mitigation and power generation implications of clean supply-side and demand-side technologies in Thailand, *Energy Policy*, 32(1). 83-90.

Thawonngamyingsakul, C. and Kiatsiriroat, T. (2012). Potential of a Solar Organic Ranking Cycle with Evacuated-Tube Solar Collectors as Heat Source for power Generation in Thailand, *Energy Science and Technology*, 4(2), 25-35.

Tongsopit, S., Junlakarn, S., Wibulpolprasert, W., Chaianong, A., Kokchang, P., & Hoang, N. V. (2019). The economics of solar PV self-consumption in Thailand. Renewable Energy, 138, 395–408. https://doi.org/10.1016/j.renene.2019.01.087.

Wang, J., Hua, C. and Li, L. (2018). Long-term Energy Sustainability Development Analysis to Reducing Carbon Emissions and Air Pollutions of China Based on LEAP Simulation Model, *Ekoloji,* 27(106), 173-179.

Yoomak, S., Patcharoen, T. and Ngaopitakkul, A. (2019). Performance and Economic Evaluation of Solar Rooftop Systems in Different Regions of Thailand, *Sustainability*, 11(23), 6647. https://doi.org/10.3390/su11236647.