Grid optimization and demand side mangement for electric vehicles penetration in remote area

Zhang, Yixiao; Ng, Eddie Yin Kwee; Li, Ning

2023

Zhang, Y., Ng, E. Y. K. & Li, N. (2023). Grid optimization and demand side mangement for electric vehicles penetration in remote area. 15th International Green Energy Conference (IGEC-XV).

https://hdl.handle.net/10356/169198

Proceedings of the 15th International Green Energy Conference
IGEC2023-000
July 10-13, 2023, Glasgow, UK

GRID OPTIMIZATION AND DEMAND SIDE MANAGEMENT FOR ELECTRIC VEHICLES PENETRATION IN REMOTE AREA

Yixiao Zhang
Nanyang Technological University
Blk 663D Jurong West St 65 #02-223, Singapore
yixiao002@e.ntu.edu.sg

Ning Li
University of Edinburgh
West Mains Road, Edinburgh, EH9 3JG
N.Li-22@sms.ed.ac.uk

Eddie Ng Yin Kwee
Nanyang Technological University
50 Nanyang Avenue, Singapore
mykng@ntu.edu.sg

ABSTRACT

The distributed power system in remote and rural area is the main challenges of the future smart grid development. Compared with traditional gasoline pipelines and gas station construction for fossil fuel vehicles, the high demand of Electric Vehicles (EVs) will then consider breaking their products in the market of remote areas. While the EVs adoption is growing globally, remote areas present unique challenges such as limited charging infrastructure, long transmission distances, and varying energy demands under the EVs penetration. This paper firstly defines the typical Remote Areas where the grid density is low with poor cable properties, but the future power demand is growing fast. Besides, their distributed energy is abundant and can contribute to generating electricity for the EVs, including solar energy, wind energy or marine energy. Renewable energy can maximize the reduction of carbon footprint and consumption. Then the Trincomalee city is selected as the simulation object.

Perform national grids simulation optimization and solar power generation management as demand side optimization. Power grid model simulation: use government data to predict that Trincomalee's electricity demand will increase from the current 40MW to 640MW in five years and build a grid simulation model for Sri Lanka's national high-voltage transmission lines. Optimization will target transmission cables that provide higher voltage loads while considering cable properties includes resistance and reactance for optimal power loss and voltage drop respectively, thermal capacity, and power quality. The results show that though a lower resistance and reactance can reduce the power loss and voltage drop during transmission, the relationship does not follow a linear relationship when integrating into the whole power system. The range of resistance and reactance scenarios is set with equal intervals. The optimal point with the higher drop scenario always exists.

The demand side management aims to solve the Trincomalee’s intermittency and overproduction issue to keep the supply and demand in dynamic balance. Solar energy production is surveyed for its intrinsic intermittency between day and night time. Based on the climatic conditions and NCRE data in the Trincomalee in 2013, the PV generation system is simulated by MATLAB and Excel and conclude the curves of solar irradiance, temperature and demand. the optimum rated capacity of the battery is then concluded from the demand and solar curve.

The case studies from Sri Land highlight successful examples of distributed grid management in remote and rural areas. The methods contribute to the broader conversation around sustainable transportation and energy systems, and to provide guidance for policymakers and industry stakeholders working towards sustainable and equitable EV adoption.

Keywords: Distributed Power Generation, Smart Grid, Power System Modelling and Optimization, Demand Side Management.

1. INTRODUCTION

Under the growing impact of climate change, Electric Vehicles (EVs) have become popular in many countries and regions due to government financial support. According to a report by the IEA (Cazzola, Gorner, M, Schuitmaker, R., & Maroney, E, 2016), there were 3.1 million electric cars in 2017, with battery electric vehicles accounting for two-thirds of the total. In particular, the penetration of EVs in urban areas or large cities has a very high demand. Most EVs are found in China, the United States, Japan, Norway, and the United Kingdom, with China having the largest number at around 1.2 million and the UK having approximately 0.15 million electric vehicles. According to the Global EV Outlook 2018, the total sales of new electric cars worldwide surpassed one million units in 2017 (Bunsen, 2018). EVs have numerous benefits for urban areas. Firstly, they can help improve air quality and reduce CO_2 emissions when the power for the cars is generated from renewable sources such as hydroelectric, wind, or solar energy. According to a report (Environmental Science and Policy 814), assuming an electric car's lifetime is 150,000 km powered by the current European electricity mix, it can reduce the total life GHG emissions by 10 to 24 percent compared to conventional gasoline-powered vehicles (Holtsmark, 2014). In summary, EVs are environmentally friendly vehicles that can increase the use of sustainable energy in large cities and improve the environment of those cities with high fossil fuel consumption. Secondly, EVs can play a significant role in adjusting the energy structure of urban transportation. Unlike conventional fuel-powered cars, EVs consume only electricity, which can be generated from diverse energy sources such as sustainable energy. As a result, the proportion of fossil fuel consumption in cities reduces, while the use of clean energy increases. Finally, with sufficient electricity supply from mature urban grids, EV charging stations can be widely distributed throughout cities. For example, in 2017, there were more than 4,700 EV charging points in London, accounting for 23.5% of the total in the UK (Christopher, 2008).

With the high demand for electric vehicles in large cities, EV companies are considering breaking into the market of remote areas. However, the penetration of EVs in remote areas is still challenging due to the limitation of network connection and supplying sufficient power. In a typical remote area, its network often lacks connection with the main grids in larger cities. Once EVs become prevalent in these areas, the transmission lines will become severely overloaded. In order to solve these problems, distributed energy generation for wind, solar or marine energy may become a popular measurement for local power supply, which is a perfect power replenishment for EVs. Additionally, electricity storage in remote areas before peak time is also a practical way of balancing power supply and demand. If there is high demand for vehicles, EV companies will consider promoting their products in the remote areas to capture their EV markets. Besides, in mountainous and coastal rock places, it is difficult for cables to collect electricity from wind turbines or PV panels to the grid system. Lastly, compared with traditional vehicles, EVs still lack enough traction driving in mountainous regions, which means more electricity consumption. Hence, they require more battery charging stations on the way of mountainous region.

This paper uses the demand-side management to assess the connection problem between the main grids and the remote areas' grid by Powerworld model, including transmission line construction, including cable capacity optimization, electricity quality assessment, and fault analysis. Then, the study also builds up a feasible solar energy storage model to balance the diurnal peak load demand by topological structures in remote areas, which can improve the reliability (and economic profit) of the off-grid power system.

2. CASE STUDY

The study chooses Sri Lanka as the case model. According to the report (Shek, 2019), a fast-economic growth and EVs penetration will occur in the coastal city called, located in the northwest of the country (Figure-1(a)). This study assumes that Trincomalee will experience a long-term increase of power demand in the next 5 years, from 40 MW in 2022 to 640 MW in 2027. As a typical remote area, Figure-1(a) shows that the power supply of Trincomalee starts from Kotmale, which serves as the slack generator in the network system and transmits through a single 220kV cable (red) to Anurad. After being transformed into a 132kV voltage, the electricity reaches Trincomalee through two 132kV transmission lines (black). Figure-1(b) demonstrates the severe blackout that occurs when an additional 600MW load is directly added in Trincomalee. The 220kV high voltage transmission line from Kotmale to Anurad will have a 129% overload, and the 132kV double cables from Anurad to Trincomalee will experience a destructive overload eight times greater than the rated load. Additionally, since the entire system is interconnected, a blackout in one cable will affect other areas as well. Moreover, this remote city does not have any fossil fuel resources for self-supply. Therefore, finding the optimal cable capacity for future network upgrading schemes is necessary.

Demand side management can optimize energy efficiency using different technical methods. These range from advanced combustion methods, sophisticated electronic control devices, to certain energy tariffs with incentives for specific consumption patterns (Palensky & Dietrich, D., 2011). The storage system is also an essential way to adjust power supply and demand. It can solve some distribution energy problems for consumers, such as intermittency and overproduction, and maintain the supply and demand in dynamic balance.

In Trincomalee, building a photovoltaic (PV) panel system is a practical way to generate electricity. The PV system can supply electricity energy directly to local residential users instead of using the grid. Moreover, the extra energy can also be integrated into the grid and generate profits. The fundamental reason for overproduction is the imbalance between ample solar energy and low demand during daylight hours. Overproduction can lead to congestion problems in the grid because the capacity of the transmission line is limited. This means that only a portion of the electricity energy can be transmitted to the grid, and the rest of the energy needs to be consumed in the local network. To solve the problem of overproduction, the remaining energy is usually discarded, or the solar panel system must be turned off.

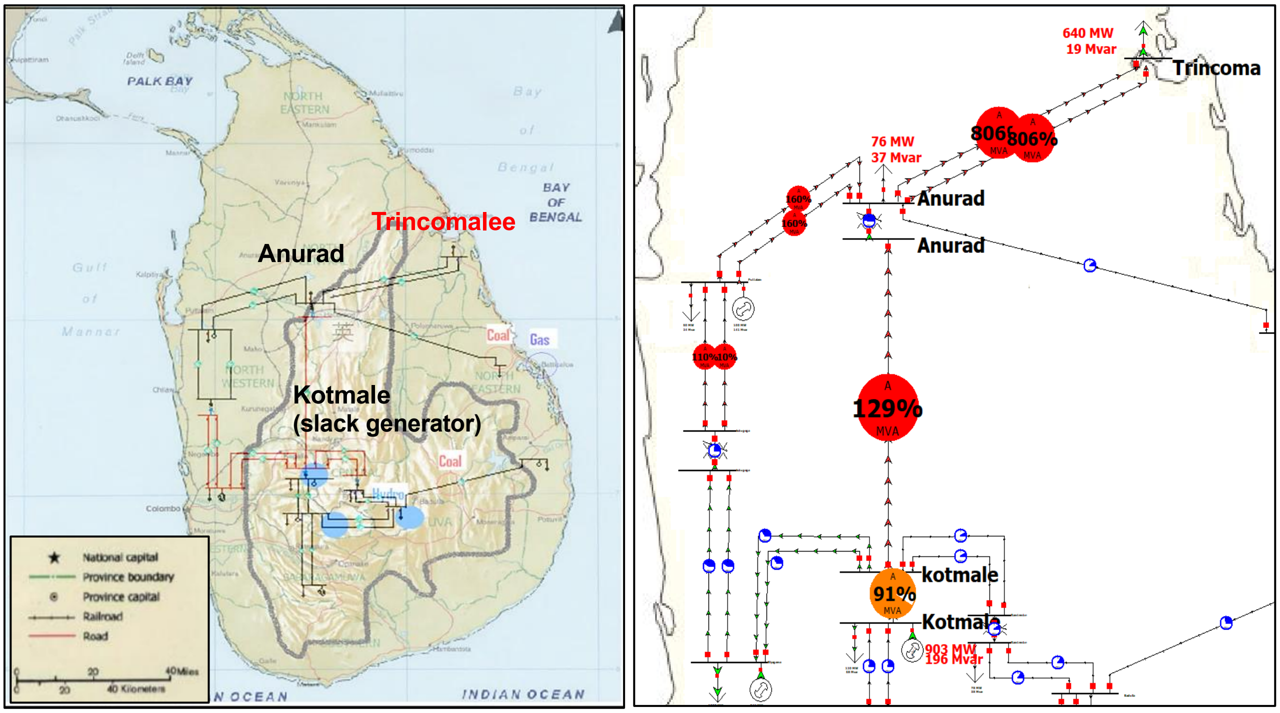


Figure 1(a) Map of Sri Lanka showing the HV network and locations of fossil fuel resources
Figure 1(b) Blackout on Trincomalee due to the fast-growing power demand

3. METHODOLOGY

3.1 Grid Optimisation

The paper focusses on those related grids from Kotmale to Anurad to Trincomalee. To run the simulation, the initial settings in Powerworld model are summarised below:

- The slack generator in the network is in Kotmale, which represents the core power supply centre;
- In 2019, the power load of Trincomalee is 40MW, then increase to 640MW in 2024;
- The power factor at each terminal side should always be greater than 0.9 to maintain the power quality;
- The cable properties from Kotmale to Trincomalee is summarized in Table 1. Noting that the transmission line properties are the old-designed ones which are required to adjust.

Table 1 Old cable properties

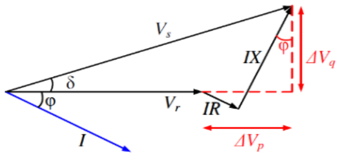
	Kotmale to Anurad	**Kotmale to Anurad**
Transmission line voltage	220 kV	132 kV
Resistance	8.31 Ω/km	2.47 Ω/km
Reactance	6.69 Ω/km	1.91 Ω/km
Thermal capacity	800 MVA	400*2 MVA

Since the varies of resistance of transmission lines will change the active power loss as shown in equation (1), the simulation aims to get a cost-effective property of cables, by varying the reactance for an optimal voltage regulation, and varying the resistance for an optimal power loss,

$$P_{loss} \approx I^2 \cdot \sum R_{line} + R_{transformer} \tag{1}$$

The magnitude and phase relationship of voltages between receiving end V_r and supplying end V_s is expressed below: (Yip, 2015)

$$V_s - V_r \approx \frac{RP + PQ}{V_r} \tag{2}$$



$$\angle V_s - \angle V_r \approx \frac{XP - RQ}{V_r} \tag{3}$$

For high voltage lines, R is often much smaller than X. Roughly, the magnitude of voltage drop is equal to , and the phase change is equal to . Therefore, the varies of reactance of transmission lines will affect the voltage drop value at receiving ends.

3.2 Demand-side management

Considering the aforementioned problems, a storage system can develop the potential of PV energy. On one hand, a storage system can solve the intermittency problem because batteries can be used as a load when there is sufficient solar irradiance. In the evening, the batteries can discharge and supply energy to consumers. The PV generation system output can be expressed as (Feng, et al., 2016):

$$P_{pv} = P_{STC}\frac{G_C}{G_{STC}}[1 + \gamma(T_C - T_{STC})] \tag{4}$$

Where P_{pv} is the PV generation system operating output, kW; P_{STC} is the PV generation system standard output, kW; G_C is the operating solar irradiance, kW/m^2; G_{STC} is the standard solar irradiance, 1 kW/m^2; γ is the temperature factor, value is -0.0043/℃; T_C is the operating temperature, ℃; T_{STC} is the standard operating temperature ℃.

In the PV system, the energy in the storage system is variable. The State Of Charge (SOC), S_t represent the energy state of battery. The state $S_{t+\Delta t}$ depends on S_t at previous t moment. The relationship between $S_{t+\Delta t}$ and S_t can be expressed as:

$$S_{t+\Delta t} = S_t + \frac{\alpha P_{bs}\Delta t}{C_{bs}U_{bs}} \tag{5}$$

Where S_t represents the energy state of battery at t moment; α is the battery efficiency (when battery is charging, the value α is 0.65~0.85; when battery is discharging, the value α is 1); P_{bs} is the charging or discharging power from t moment to $t + \Delta t$ moment (when battery is charging, the value P_{bs} is positive; when battery is discharging, the value P_{bs} is negative); C_{bs} is the battery rated capacity, kWh; U_{bs} is battery rated voltage, V.

In order to protect the battery, the SOC at any moment needs to be limited to a certain range. The SOC range can be expressed as:

$$S_{OC\,min} \leq S_t \leq S_{OC\,max} \tag{6}$$

Where S_{OCmin} is the lower limit of SOC; $S_{OC\,max}$ is the upper limit of SOC.

In addition, due to the limitation of battery current, the battery should be charged and discharged within 20% of the rated capacity of the battery at a time when the voltage is constant, that is:

$$-0.2C_{bs} \leq P_{bs} \leq 0.2C_{bs} \tag{7}$$

The main parameters of PV panel and battery are showed in the Table 2:

Table 2 The main parameters of PV pane and battery

Parameters of PV pane	Value	Parameters of battery	Value
Open-circuit voltage/V	21.0	Rated capacity/(kWh)	0.4
Short-circuit current/A	5.7	Rated voltage/V	2.0
Maximum power/W	100	SOC lower limit	0.2
Temperature factor γ/%	0.43	SOC upper limit	1.0
		Charging efficiency	0.75

Based on the climatic conditions and NCRE data in the Trincomalee in 2013, the PV generation system is simulated by MATLAB and Excel. The data about the Trincomalee is represented in the (Weather station: Trincomalee, 2013). The annual total NCRE generation is 1179 GWh, which includes mini-hydro, wind, biomass and solar energy. Solar energy occupies 4.69 GWh (0.39%) of the annual total NCRE generation in 2013. According to the solar irradiance, temperature, and demand data in one day (Resource Management Associates (RMA) Pvt., 2013), combined with the two models and constraint conditions above, the curves of solar irradiance, temperature and demand are simulated at Figure 2 below:

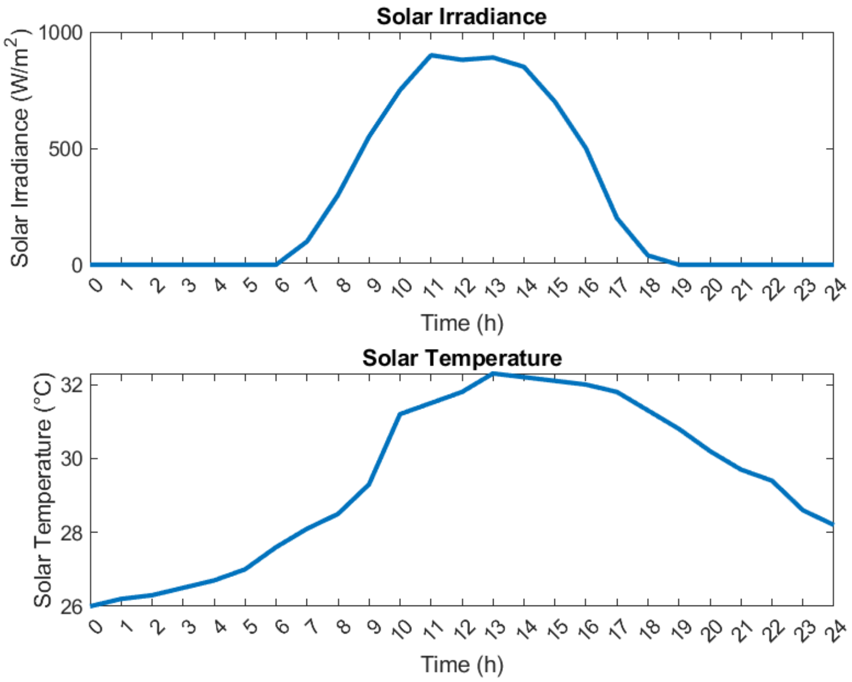


Figure 2 Curves of solar irradiance, temperature, and demand

The maximum capacity determines the PV energy efficiency and stored capacity. This paper simulated 0.20-0.45 kWh maximum capacity of the battery.

4 RESULTS

The report aims to model the city's network condition in Powerworld, including simulating different cable thermal capacities and impedance; then record 1) the cable load on the two transmission lines, 2) voltage fluctuation in Anurad and Trincomalee, 3) power factor changes; next will do the fault analysis to test the new cables' reliability. The optimal cable property can be a practical mitigation of upgrading the grids scheme.

4.1. Power loss and voltage drop optimisation

Table 3 records the line resistance and reactance changes from Kotmale to Anurad. The interval of changes is fixed at 1.0×10^{-5} Ω/km for R and 1.0×10^{-4} Ω/km for X. Then we calculate the power loss and voltage drop between Kotmale and Anurad and draw the trending line curve at Figure 3. In the line curve of Figure 3, the scenario 3 has an obvious decrease on both power loss and voltage drop. Before and after this point, both the power loss and voltage drop change smoothly; therefore, considering about the economic restriction and the material of cable, this report plans to choose the scenario 3 as the new transmission line's properties from Kotmale to Anurad.

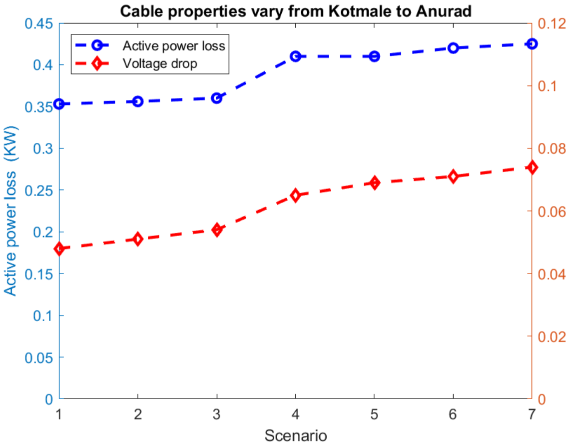
Table 3 Cable R and X changes from Kotmale to Anurad

Parameters	220kV From Kotomale to Anura						
Scenario	1	2	3	4	5	6	7
R/km	0.000053	0.000063	0.000073	0.000083	0.000093	0.000103	0.000113
X/km	0.000369	0.000469	0.000569	0.000669	0.000769	0.000869	0.000969
Active power loss	0.353	0.356	0.36	0.41	0.41	0.42	0.425
Voltage drop	0.048	0.051	0.054	0.065	0.069	0.071	0.074

Similarly, based on this cable properties, the Powerworld simulate the changes of resistance and reactance from Anurad to Trincomalee and record them in Table 4, with interval of 1.0×10^{-5} Ω/km for R and 2.0×10^{-4} Ω/km for X. Then based on Figure 4, we choose the scenario 5 as the new cable properties.

Table 4 Cable R and X changes from Anurad to Trincomalee

Parameters	220kV From Anura to Trincomalee						
Scenario	1	2	3	4	5	6	7
R/km	0.000018	0.000020	0.000022	0.000024	0.000026	0.00028	0.00030
X/km	0.000131	0.000151	0.000171	0.000191	0.000211	0.000231	0.000251
Active power loss	0.3	0.32	0.34	0.36	0.38	0.42	0.44
Voltage drop	0.105	0.111	0.117	0.123	0.128	0.138	0.144



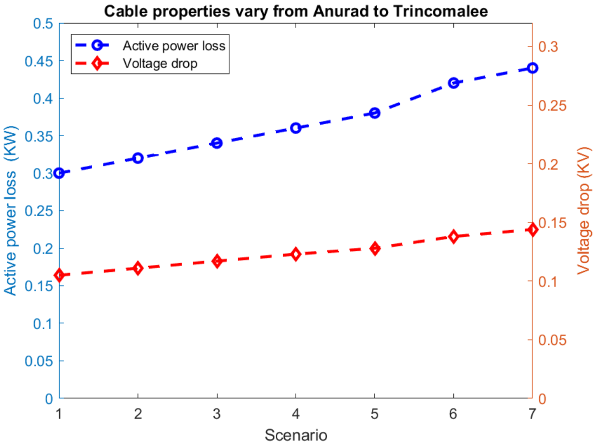


Figure 3 (left) Line curve of the active power loss and V drop changes from Kotmale to Anurad
Figure 4 (right) Line curve of the active power loss and V drop changes from Anurad to Trincomalee

The main method to improve the power quality is to shunt a capacitor with a proper value on the bus where power factor is lower than 0.9. From the Table 6, the bus of Anurad is required to improve its power factor by a shunt capacitor. In Powerworld, the value is chosen at 58 MVAr.

Table 6 Power factor rectification

	Kotmale	Anurad	Trincomalee
Active power / MW	897.61	76.1	640
Reactive power / MVar	116.85	37.4	18.7
Power factor	0.992	0.897	1.00
Shunt capacitor / MVar	No need	57.987	No need

Figure 5 is the final network working condition. The cables and transformers from Kotmale to Anurad and to Trincomalee all satisfy the fault analysis requirement. The power factor on each bus is regulated, and the power loss and voltage drop have been set at a cost-effective value. The supply side simulation and analysis support a safe and stable network.

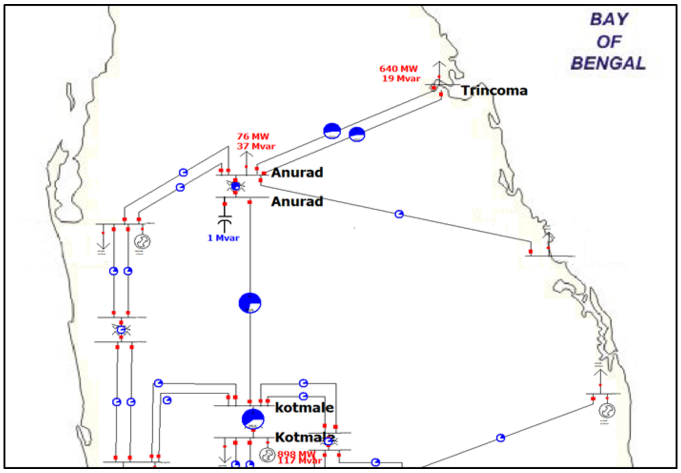


Figure 5 Upgraded power system from Kotmale to Trincomalee

4.2 Result of demand-side storage system

The result shows the battery with higher capacity can save more fossil fuel energy. When the capacity of battery increases, the fossil fuel generator output decreases. The reason is that the battery can supply the stored energy to consumer at night instead of using fossil fuel generator. In addition, the battery with higher capacity can also store more energy in one day. It can solve the overproduction problem. The reason is that the battery with high capacity can still store energy at noon instead of wasting solar energy. This is the main difference from the battery with lower capacity. From Figure 6, the battery with high capacity does not hit the maximum limit, but the battery with low capacity will in saturated state at noon, which means it wastes the solar energy.

However, the battery with higher capacity is more expensive, and the stored efficiency for the system will also decrease. For instance, in this condition, the effects of 0.5 kWh and 0.6 kWh are similar, because the solar irradiance and temperature are fixed relatively in one location. Figure 7 indicates four batteries with different capacities. The area between the curve and X-axis could represent the total stored energy per day. Therefore, the optimum rated capacity of the battery is approximately 0.4 kWh in this condition. In addition, the optimal capacity of battery also depends on the starting state of charge, the local climate condition, and other local distributed energies.

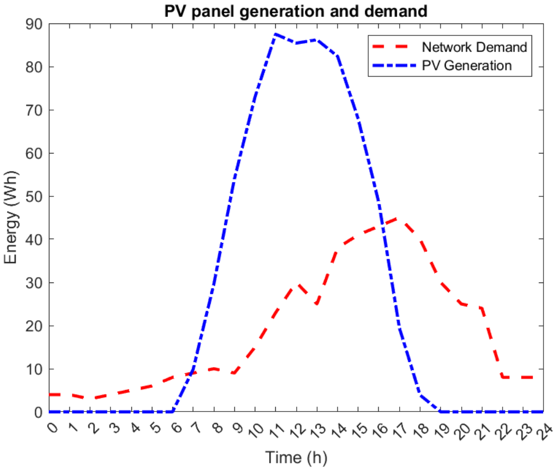


Figure 6 PV panel generation and demand

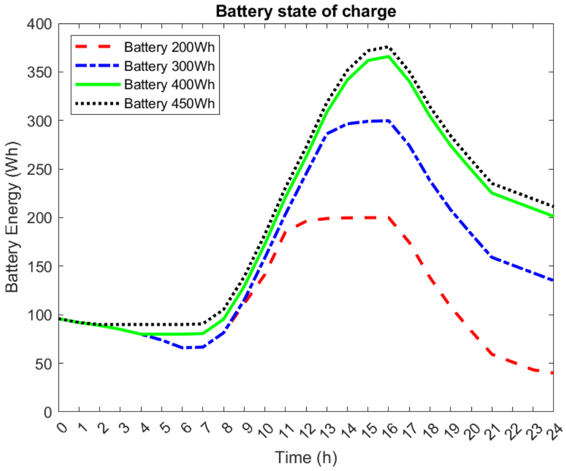


Figure 7 Different Batteries' stored performance

Based on the cable analysis and demand side management, building up distributed energy network is practical to mitigate the increasingly demand in the future. On one hand, the distributed energy network cable capacity and storage system can be optimised through the analysis above. On the other hand, since remote areas, such as Trincomalee, usually site in mountainous or coastal regions where solar, wind and marine energy have adequate potential, it facilitates the development of the local distributed energy network. Moreover, those remote areas building up the new network will be increasingly independent of the national grid's load restriction to operate a self-supporting grid system.

6. Conclusion

To conclude, the penetration of EVs in remote area leads to growth of power load, which requires balancing the relationship between electricity supply and demand. On supply side, simulating the grid mechanism to find the optimal new cable properties is the one effective way. On demand side, the technology of demand side management will instruct a cost-effective capacity for storage system. Furthermore, based on the supply and demand side analysis, the local distributed network system can be implemented scientifically and maximise the sustainable energy potential. However, upgrading grid cannot go without the society and policy's support. If in the future, every family user and grid operator can cooperate to support the project, then a stable and mature smart grid can benefit the remote area where electrical vehicles and other high-electricity consuming project will happen.

ACKNOWLEDGEMENT

The authors would like to offer their appreciation and thanks to Collaborative Initiative, Interdisciplinary Graduate Programme, Nanyang Technological University, Singapore for the support in computing facility in model optimization and IGP scholarship. We also deeply appreciate the software facility provided by University of Edinburgh during the entire paper preparation.

NOMENCLATURE

ρ	density, kg/m^3	V_r	Receiving end Voltage
c_p	specific heat, J/kg°C	V_s	Supplying end Voltage
h	heat transfer coefficient, W/m$^{2\circ}$C	X	Reactance
P	Active power	EV	Electric Vehicle
Q	Reactive power	PV	Photovoltaic
R	Resistance	SOC	State of Charge

REFERENCES

Aphornratana, Satha, and Thanarath Sriveerakul. "Analysis of a Combined Rankine–Vapour–Compression Refrigeration Cycle." *Energy Conversion and Management*, vol. 51, no. 12, Dec. 2010, pp. 2557–2564, https://doi.org/10.1016/j.enconman.2010.04.016. Accessed 24 Sept. 2021.

Camara, Youssouf, et al. *Electric Vehicles, Tax Incentives and Emissions: Evidence from Norway*. International Monetary Fund, 8 June 2021.

Chianelli, Russell R, et al. "Fundamental Studies of Transition-Metal Sulfide Catalytic Materials." *Advances in Catalysis*, vol. 40, 1 Jan. 1994, pp. 177–232, https://doi.org/10.1016/s0360-0564(08)60658-6. Accessed 4 July 2023.

D Yogi Goswami, et al. *Principles of Solar Engineering*. Philadelphia, Pa, Taylor & Francis, 2000.

Dahlquist, Erik, et al. "Alternative Pathways to a Fossil-Fuel Free Energy System in the Mälardalen Region of Sweden." *International Journal of Energy Research*, vol. 31, no. 12, 2007, pp. 1226–1236, https://doi.org/10.1002/er.1330. Accessed 10 Apr. 2023.

https://www.howstuffworks.com/hsw-contact.htm. "How Electric Car Batteries Work." *HowStuffWorks*, 18 Aug. 2008, auto.howstuffworks.com/fuel-efficiency/vehicles/electric-car-battery.html. Accessed 4 July 2023.

Li-aung, Yip. "Electrical Engineering." *Electrical Engineering Stack Exchange*, 2015, electronics.stackexchange.com/questions/188378/transmission-lines-voltage-drop. Accessed 4 July 2023.

Sustainable Energy Authority of Sri Lanka , Ministry of Power and Energy. *Technical Assistance Consultant's Report Final Report: Part 2 (Wind and Solar Resource Assessment) SRI LANKA: Clean Energy and Network Efficiency Improvement Project*. 2013.

Till Bunsen, et al. *Global EV Outlook 2018: Towards Cross-Modal Electrification*. 1 Jan. 2018. Accessed 4 July 2023.

"Weather in August 2013 in Trincomalee, Sri Lanka." *Www.timeanddate.com*, www.timeanddate.com/weather/sri-lanka/trincomalee/historic?month=8&year=2013#.