REDUCING AIR CONDITIONING ELECTRICAL DEMAND IN HOT ARID CLIMATES USING PV: A CASE STUDY IN JEDDAH, SAUDI ARABIA

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Abstract

Kingdom of Saudi Arabia (KSA) is one of the rich sunbelt countries in the world with very large potential for deploying solar photovoltaic (PV) technologies to support transitioning its dependence on fossil fuel dominated electricity sector. The hot arid climate of the country combined with its growing per capita income and cheaper electricity tariff makes KSA having the third largest electrical cooling load in the world. This research investigates how appropriately sized residential rooftop PV system can reduce such a load in KSA's residential sector addressing sustainability and emission reductions. Modelling was carried out to determine the efficacy of an optimally sized grid connected PV system to support different scenarios of the air conditioning loads of a monitored villa in Jeddah where the electrical demand was measured over a period of one year. Techno-economic suitability of the proposed system was analysed within the remit of Electricity Cogeneration and Regulatory Authority's (ECRA) current policy and regulatory framework for small scale solar PV systems. The results show that for a daytime load scenario in the range 33 to 95 kWh/d with an average of 76 kWh/d, a 15 kWp PV array can be used to displace at least 99% of all the daytime electrical loads including cooling loads. However, the economic analysis indicates that without support mechanisms, the longer payback period for the PV system may hinder the uptake of rooftop PV integration in Saudi residential sector.

Keywords: Rooftop PV, displacing cooling load, net metering, payback period, return on investment

1. Introduction

Residential buildings in the Kingdom of Saudi Arabia (KSA) consume 46% of the total electrical demand of the country (KAPSARC 2018), and almost 70% of such consumption comes from cooling loads (Mujeebu and Alshamrani 2016). The persistent hot arid climate of the country combined with its growing per capita income and cheaper electricity tariff made KSA the third largest electrical cooling load consumer in the world (Al-Badi and AlMubarak 2019). KSA is one of the rich sunbelt countries with huge potential of deploying solar photovoltaic (PV) technologies to sustainably transition its fossil fuel dominated electricity sector to low carbon based on renewable energy. Despite such solar resources potential, in the electricity sector, PV only contributes about 433 GWh compared to 385,100 GWh by oil and natural gas in 2019 (Figure 1). Furthermore, KSA's per capita electricity consumption has been increasing annually reaching over 10 MWh in 2019 (Figure 1) (IEA 2020). To meet Saudi government's new renewable energy target of 27.3 GW by 2023 and 57.8 GW by 2030, as part of its 'Vision 2030' strategy, solar photovoltaics could play a vital role (Climate Action Tracker, 2020).

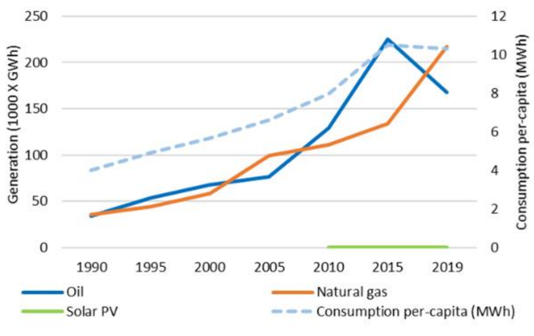

Fig. 1: Electricity generation by source in Saudi Arabia between 1990 and 2019, and growth in per capita electricity consumption during this period (Adapted from IEA 2020)

Integration of domestic rooftop PV would bring power directly to where it is consumed, in contrast to large solar farms located outside cities. As the year-round residential peak cooling demands in Saudi residential sector are spread over the period between 11am and 5pm (Alshahrani and Boait 2018), this can be supported

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Selection and/or peer review under responsibility of Scientific Committee
doi:10.18086/swc.2021.45.01 Available at http://proceedings.ises.org

by the PV power generated during this period without having the need for any expensive energy storage. This approach offers a great potential for Saudi housing sector to embrace PV power generation for self-consumption to displace cooling loads.

This work investigates how residential rooftop PV can support reducing grid-based air conditioning loads of a monitored case study building in Jeddah. The research presented here addresses the growth of rooftop PV supported by financial incentive tools in Europe and current policy frameworks for such PV systems in Saudi Arabia in Section 2, followed by the description of the methodology applied here (Section 3), the results and discussions in Section 4 and conclusions in Section 5.

2. Rooftop PV to support domestic loads

Global rooftop solar PV market size reached a value of USD 66.84 billion in 2019, and its installed capacity share recorded almost 13% of total PV installed in 2021 (IEA 2021). Residential rooftop PV for self-consumption and exporting any excess power generation to the utility grid has been promoted in many countries since late 1980. Many countries in Europe (e.g. Germany, Denmark, Spain, Italy) were the early adaptors of lucrative `feed in tariff'(FiT) to enhance the uptake of residential PV dissemination (González 2008, Munksgaard and Morthorst 2008, and Deutsche Bank 2011). While the UK had seen the successful uptake of rooftop PV installation driven by FiT in 2008, France and Italy witnessed the highest growth in this sector in 2011 and 2012 respectively (Zhang et al., 2016). Besides, having a suitable FiT in place, appropriate policy framework is crucial to support the target dissemination of residential rooftop PV in any country. Through appropriate policy support and FiT, the UK for example had installed residential PV which generated 3.5TWh of electricity in 2016 (OFGEM 2017). While the FiT scheme in the UK ended in 2019, the Smart Export Guarantee (SEG), a government supported scheme was launched on 1 January 2020 to support such residential micro generations (OFGEM 2020). Applicable tariff for the electricity exported to the grid by the residential PV system under the SEG scheme varies with different energy supplier (licensee) of that residential customer (OFGEM 2019). According to Solar Energy UK (2021), SEG tariff varies from USD 0.021/kWh (offered by EDF Energy) to USD 0.15/kWh (offered by Tesla Energy through Octopus Energy provided that customers use Tesla Powerwall battery as storage).

2.1 Rooftop PV in Saudi Arabia

In 2017, a study on utilising the roofs of buildings in KSA has shown that, for the 13 cities considered, an annual combined potential of 51TWh from rooftop PV is feasible. This translates to about 30% of the domestic electricity demand (Khan et al., 2017). However, to date installed PV capacity in Saudi housing sector is negligible. To boost residential rooftop PV utilisation at a scale the Electricity and Co-generation Regulatory Authority (ECRA) in Saudi Arabia updated its Regulatory Framework for Small Scale Solar PV Systems in 2019 (ECRA 2019). Under this framework, PV systems with capacities between 1kWp and 2MWp are eligible to be connected to the utility grid through the local distribution service provider (DSP) under the following key terms:

(i) DSP shall provide the net metering to the eligible residential customers provided that the aggregated capacity of small-scale solar PV to be connected to the utility grid shall not exceed 3% of the preceding year's peak load of the power system within its distribution operating area, and shall not exceed 15% of the rated capacity of the distribution transformer from which the load of the consumer is fed.

(ii) In the case of large residential buildings (e.g. villas), which may have multiple meters, net metering arrangement by the DSP shall be done at one exit point linked to only one single meter, not to several consumption meters.

(iii) While, under the current ECRA residential customer tariff slabs, customers with monthly consumption less than 6 MWh pay USD 0.048/kWh, and customers consuming 6 MWh or more each month pay USD 0.08/kWh (ECRA 2018), any eligible customer will get paid USD 0.02/kWh as feed in tariff (FiT) for any extra electricity generated and exported to the utility grid by the PV system regardless of their monthly consumption volume.

Stated cap on maximum installed PV capacity limits related to different DSP network areas by the ECRA's regulation may discourage potential early adaptors in installing bigger capacity PV systems. As the residential electricity tariff is cheaper in Saudi Arabia and it is well below the international market level (Aldubyan and Gasim 2021), residential customers may not be motivated to invest into rooftop solar. It is therefore, very important to analyse the suitability of such distributed generation under the policy and regulations and identify the challenges to inform the policy makers.

3. Methods

Installation of residential rooftop PV to support household loads in full or partially is a well-accepted technology application for using solar resources across the world, and the technology itself is well matured. However, uptake of such residential PV systems at national level depend on several interrelated factors, such as: (i) applicability of the technology at local context, (ii) financial attractiveness (i.e., incentive, subsidy, feed in tariff) (iii) policy support and effectiveness, and (iv) awareness (Ahang et al., 2014, Zeineb et al 2015, Mundaca and Samahita 2020, Linda et al. 2020).

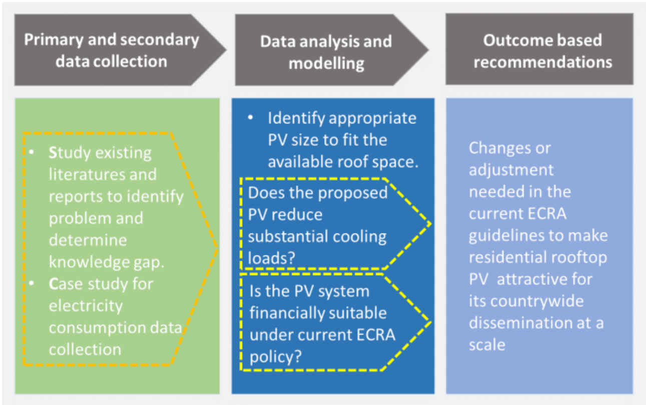

Fig. 2: Methodological framework for studying the potential of rooftop PV in reducing electrical cooling loads in Saudi residential sector

To investigate the potential of residential rooftop PV in reducing domestic air conditioning loads in Saudi Arabia, a methodological framework depicted in Figure 2 was developed. This framework embeds real data on consumption from a case study building in Jeddah. The data gathered through deployed monitoring systems underpins the PV system modelling and analysis and the techno-economic assessment based on existing policy regime in KSA.

The overall steps followed in the methodology to arrive at the system and economic recommendations are presented in Figure 3.

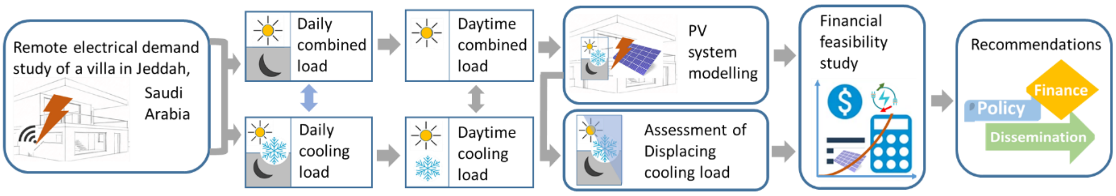

Fig. 3: Sequential steps of the study to investigate the potential of rooftop PV in reducing air conditioning electrical demands in Saudi housing sector

Electricity consumption data of the villa in Jeddah which consist of three floors with separate meters were remotely monitored for over a year with data captured at ~30 sec resolutions to understand daily and seasonal variations in loads. Here we only consider the 1st floor energy consumption data to model appropriate PV system, as this floor presents the main living area of 300 m^2 and highest cooling loads among three floors of the villa. The consumption data of this floor is termed 'study consumption' in the rest of the paper.

Simulations were carried out using a modelling software (HOMER Grid) to determine, (a) the ability of different PV system sizes that can support the air-conditioning loads only, and (b) how much the designed PV system could contribute to other loads, for the study consumption (first floor only). The optimum PV system is derived through the modelling, and an appropriate design of the system was developed so that it can be integrated to the existing electrical wiring of the villa. In addition, an economic assessment of the cost of installation for financial feasibility study of the proposed PV system was also carried out through the modelling based on the market cost of PV system components taking into account of the current Electricity Cogeneration and Regulatory Authority's (ECRA) policy and regulatory framework for small scale solar PV systems. For the economic analysis of the final designs of the PV system, it was assumed that no interest to be paid on the initial investment. However, a fixed amount of USD 3000 for replacement and maintenance was included in estimating the potential savings on electricity bills over 25 years of the PV system's operational life. Based on the combined outcomes of the techno-economic analysis appropriate policy and financing recommendations are made to support the utilisation of rooftop PV in KSA.

4. Results and discussions

In the study consumption case (1st floor of the villa) the electrical loads varied between 66 kWh in February and 167 kWh in June, with May and July presenting almost similar average daily load of 150 kWh (Figure 4). Total daily (day and night) electricity consumption (i.e. cooling, lighting, hot water, entertainment, other) and the daytime only consumption of the 1st floor of the villa at different months of the year showed similar pattern in load variation (Figure 5). This is due to the fact that cooling loads dominate the electricity consumption of this floor. While daily (day and night) AC (cooling) loads varied between 46kWh/d in February and 117 kWh in June, daily daytime only AC (cooling) loads varied from 24.5kWh in February to 64kWh in June (Figure 5).

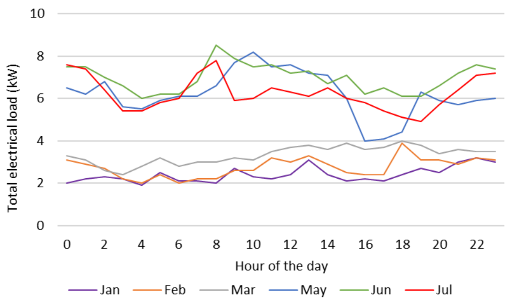

Fig. 4: Hourly average electrical loads (kW) for the study consumption (1st floor of the villa) for six months representing three highest and three lowest months

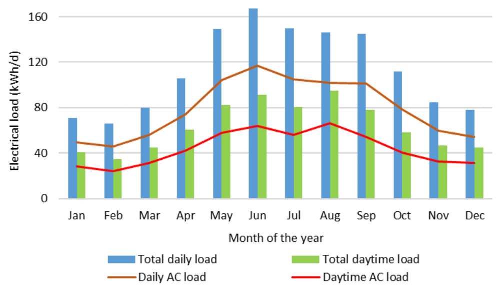

Fig. 5: Average daily electrical loads (total load, total cooling load, total daytime only loads and total daytime only cooling loads for the study consumption (1st floor of the villa)

Table 1 shows the annual data for the monitored electrical demand for the 1st floor (study consumption) indicating a total daily (day and night) load of 39.4 MWh/y, daytime only total load of 23.1 MWh/y, daily cooling load of 29 MWh/y and daytime only cooling load of 16 MWh/y. This indicates that the evening load is about 16.3 MWh/y (=39.4 – 23.1). According to ECRA, the tariff for this residential customers is USD 0.048/kWh as the study consumption (1st floor) load is below the 6 MWh/m threshold (Table 1) (ECRA 2018).

Table. 1: Yearly electricity consumptions of the study consumption (1st floor). For this range the applicable consumption tariff is USD 0.048/kWh

Load type	Load
Total daily load	39.4 MWh/y
Daytime only total load	23.1 MWh/y
Daily cooling load	29 MWh/y
Daytime only cooling load	16 MWh/y

Figure 6 presents the efficacy of different size of grid connected PV systems modelled to serve various load scenarios of the study consumption without energy storage. The results show that modelled PV systems below the capacity of 10 kWp were able to serve ≤50% of daytime loads, and significant shortfalls in serving cooling loads were evident in this range (Figure 6). However, the modelled 15 kWp PV system outperformed its close capacity options of 14 kWp and 17 kWp as it is able to serve 99% of the total daytime loads as well as full daytime cooling loads. Therefore, the 15 kWp PV system is considered as the optimum system size to fully support the study consumption (1st floor of the villa).

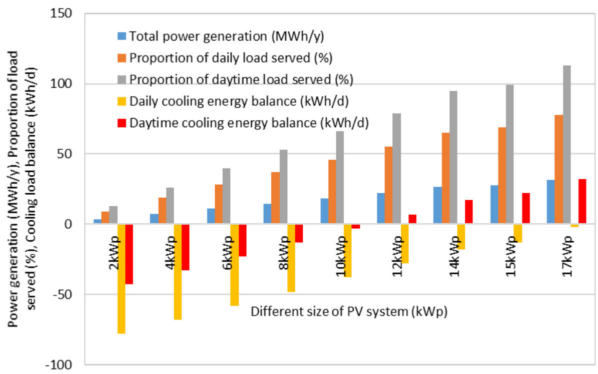

Fig. 6: Efficacy of different size of PV systems serving the total load including air conditioning loads for the study consumption case.

Figure 7 shows the results of the seasonal variation in power generation by the 15 kWp PV system in comparison to the variations in total electrical loads of the study consumption (1st floor). With the annual PV power generation of 27.2 MWh, the 1st floor of the villa (study consumption) needs to import 12.2 MWh each year from the utility grid to meet the total demand of 39.4 MWh/y (Figure 7). As the daytime only load is 23.1 MWh/y (Table 1) and the PV system does not have any energy storage, the excess amount of 4.1 MWh/y energy is exported to the grid.

Under the current net metering provision of ECRA, if the 1st floor of the villa (study consumption) is billed on a monthly cycle, the villa consumer will pay USD 0.048/kWh for the amount of electricity it imports from the grid, and will get paid USD 0.02/kWh for the excess power it exports to the grid by the 15 kWp PV for the months it remains as net exporter.

Based on the structure of the roof, its layout and available shadow-free area, a 15 kWp gravity mount grid connected three phase PV system is designed which can be integrated into the existing electrical wiring of the household (Figure 8). The cost of the system including installation was estimated to be USD 17,500 (Table 2).

Considering the yearly daytime electrical demand (23.1MWh; Table 1) served by the 15 kWp PV at an import tariff of USD 0.048/kWh, and total energy exported to the grid (4.1MWh/y) at an export rate of USD 0.02/kWh, the study consumption (1st floor) saves ~USD 1180 ((23MWh/y x USD 0.048/kWh = ~USD1100) + (4.1MWh/y x USD 0.02.kWh = ~USD80)) each year on its electricity bill. Without having the rooftop PV installed, this household would have paid electricity bill of USD 1890/y (39.4MWh x USD 0.048/kWh). Therefore, with the proposed 15 kWp PV system installed, this villa will have a yearly electricity charge of USD 710 (=1890-1180) for the study consumption to serve its total demand of 39.4 MWh/y.

Figure 9 presents estimated payback period for the 15 kWp PV system for the study consumption (1st floor) load scenario based on the electricity bill savings (USD 1180/y) as indicated above. The figure also shows the amount of savings on electricity bill over the life of the project. Under the current applicable electricity tariff (USD 0.048/kWh) of the study consumption (1st floor), where total cost of the proposed PV system (USD

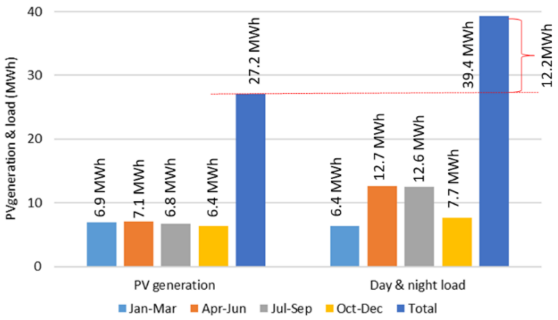

Fig. 7: Seasonal variations in power generation by the proposed 15kWp PV system in comparison to the total electrical demand variation of the study consumption (1st floor) during the similar periods of the year.

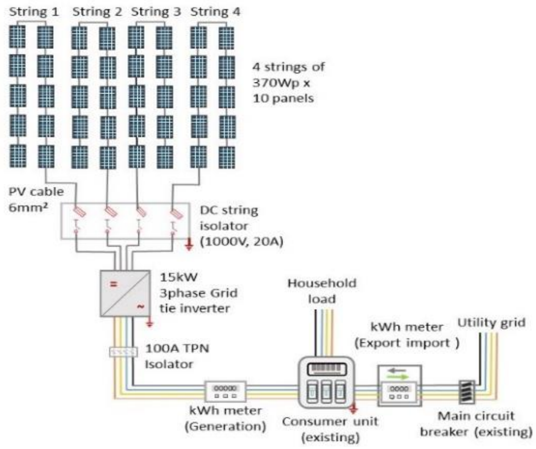

Fig. 8: Architecture and components of a 15kWp grid connected PV system for the study consumption

Table. 2: Estimated cost (components and installation) of the 15kWp three phase grid connected PV system for the study consumption (1st floor of the villa). ***PV system life 25 years.***

Item	Cost (USD)
PV 370Wp each x 40 panels	7200
Inverter 15kW (grid tie, 3 phase)	2500
DC Switch gears & cables	1600
AC Switch gears & cables	1400
Gravity mount & structure	3000
Permission, installation & metering	1800
Replacement & maintenance cost	3000
Total cost of the system	17500

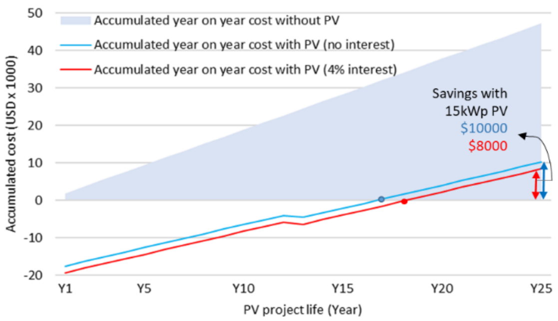

Fig. 9: Cost of electricity for the study consumption (1st floor) with and without the 15kWp PV system installed over 25 years.

17500) is paid upfront (0% interest), it recovers the investment in the 16th year. Furthermore, in such investment scenario, the amount of savings over 25years is ~USD 10,000 (Figure 9). If an interest rate of 4% is considered on the investment of the PV system assuming USD 17500 to be repaid in 5 years, recovery of the cost defers to 18th year. The saving over the life of the project, in this case is reduced to ~USD8000 (Figure 9).

The estimated payback period of 16 years for the proposed 15 kWp PV system in the case of the study consumption (1st floor) load is considerably too long to encourage residential customers to invest in such rooftop PV systems.

However, such PV interventions are likely to make the investment worthwhile especially for large consumers. For the case of a residential customer with monthly consumption of 6 MWh or higher, the day time load will be larger than the study consumption (1st floor) and all power generated by the same proposed PV system will be self-consumed by the customer leaving no export to grid. The import tariff for such customer is USD 0.08/kWh, which translates into an electricity bill savings of ~USD 2175/y (27.2MWh/y load served by the PV system x USD 0.08/kWh consumption tariff) and the payback period for proposed 15 kWp PV system is around 8 years considering no interest on investment. The total savings over 25years in such case is ~USD 34000 (($2175 x 25y) – (Investment = $17500 + $3000 for O&M and replacement 13th year)).

Payback period for the proposed 15 kWp PV system for the larger consumer (import tariff at USD 0.08/kWh) mentioned above is halved when compared with the study consumption case where the import tariff USD is 0.048/kWh. This means that under the current consumption and feed in tariff regime, rooftop PV installation will be more attractive to the higher electricity consuming customers.

5. Conclusion

The Kingdom of Saudi Arabia (KSA) is one of the rich sunbelt countries with very large solar resource, appropriate for solar photovoltaic energy conversion deployment. This is important at the housing level, where the hot arid climate of the country combined with its growing per capita income and cheaper electricity tariff is driving electrical cooling demand resulting in the country having the 3rd largest cooling load consumption in the world. Intervention of PV power generation at the housing level has many advantages, including reduced transmission losses, but more importantly bringing power generation at the point of use (Bahaj and James 2007).

Hence, in order to address such cooling loads at the residential housing level, this work presented an investigation in identifying appropriately sized residential rooftop PV systems that can reduce such loads under the weather conditions of KSA. Furthermore, the presented results were based on real data obtained through yearly monitoring of the electrical consumption of different floors of a case study villa in Jeddah. The modelling identified an optimum design of 15 kWp PV system that can serve 99% of the annual daytime loads including cooling of the villa represented by the 1st floor. The designed system was also capable of contributing additional power to support other daytime loads in the villa. Increasing the size of PV system to greater than 15 kWp would have resulted in oversizing the system under the current applicable import tariff of USD 0.048/kWh and feed in tariff of USD 0.02/kWh if an energy storage system is not used. On the other hand, adding energy storage to the PV system would increase the cost, and financially the system may not be viable.

The results show that a payback period for such a system and considered load is of the order of 16 years, which is too long to encourage residential customers to invest in such systems. However, for large consumers such interventions are likely to make an investment worthwhile especially for the higher import tariff of USD 0.08/kWh. This means that under the current consumption and feed in tariff regime, rooftop PV installation will be more attractive to the higher electricity consuming customers. Nevertheless, it is anticipated that the import tariffs will rise year-on-year and some form of incentives will be announced in KSA in the near future. This is likely to scale up the utilisation of PV on buildings in KSA.

6. Acknowledgement

This work is part of the activities of the Energy and Climate Change Division (ECCD) and the Sustainable Energy Research Group (SERG) in the Faculty of Engineering and Applied Sciences at the University of Southampton (www.energy.soton.ac.uk), UK, and the Department of Electrical and Computer Engineering, King Abdulaziz University (KAU), Saudi Arabia. The work is funded by the Ministry of Education in Saudi Arabia through project number 714, coordinated through the Deputyship for Research and Innovation, KAU.

7. References

Ahang, H. L., Gerven, T. V., Baeynes, J. and Degreve, J., 2014. Photovoltaics: Reviewing the European Feed-in -Tariff and Changing Efficiencies and costs. Sci. Worl. J. doi.org/10.1155/2014/404913.

Al-Badi, A and AlMubarak, I., 2019. Growing energy demand in the GCC countries, Arab J. of Basic and Appl. Sci. 26(1), 488-496. DOI: 10.1080/25765299.2019.1687396

Alshahrani, J. and Boait, P., 2018. Reducing high energy demand associated with air conditioning needs in Saudi Arabia. Energies. 87(12). doi.10.3390/en12010087.

Bahaj A. S., and James, P. A. B., 2007. Urban energy generation: The added value of photovoltaics in social housing, *Renewable and Sustainable Energy Reviews*. 11(9). Pp 2121-2136.

Climate Action Tracker, 2020. Saudi Arabia. Available at: https://climateactiontracker.org/countries/saudi-arabia/ [accessed 03.04.2021]

Deutsche Bank, 2011. The German Feed-in Tariff for PV: Managing Volume Success with Price Response, Deutsche Bank Climate Change Advisors Report.

ECRA, 2018. Residential consumer tariff- Saudi Arabia. Available at: https://www.ecra.gov.sa/en-us/ECRARegulations/ElectricityTariff/Pages/Tariffconsumption.aspx [accessed 12.10.2021]

ECRA, 2019. Regulatory Framework for Small Scale Solar PV Systems, ERD-TA012 (V02/19). Electricity and Co-generation Regulatory Authority, Kingdom of Saudi Arabia.

IEA, 2020. Electricity generation by source, Saudi Arabia 1990-2019, International Energy Agency. Available at: https://www.iea.org/fuels-and-technologies/electricity [accessed 12.08.2021]

IEA, 2021. Shares of solar PV net capacity additions by application segment- 2013-2022, IEA, Paris. Available at: https://www.iea.org/data-and-statistics/charts/shares-of-solar-pv-net-capacity-additions-by-application-segment-2013-2022 [accessed 05.09.2021]

González, P. R., 2008. Ten years of renewable electricity policies in Spain: an analysis of successive feed-in tariff reforms, En. Pol. 36(8), 2907–2919.

HOMER Grid. HOMER Energy: Distributed Generation. Information available at: https://www.homerenergy.com/products/grid/index.html

KAPSARC, 2018. Electricity consumption by sectors, King Abdullah Petroleum Studies and Research Centre. Available at: https://datasource.kapsarc.org/explore/dataset/electricity-consumption-by-sectors/cross-table/ [accessed 23.05.2021].

Khan, M, Asif, M. and Stach, E., 2017. Rooftop PV potential in the residential sector of the Kingdom of Saudi Arabia, Buildings. 2. 46.

Linda B., Debbie, H. and Janet, S., 2020. Solar electricity cultures: Household adoption dynamics and energy policy in Switzerland, En. Res. & Soc. Sci. 63, ISSN 2214-6296.

Mujeebu, M.A., Alshamrani, O.S., 2016. Prospects of energy conservation and management in buildings: The Saudi Arabian scenario versus global trends. Renew. Sustain. Energy Rev. 58, 1647–1663.

Mundaca, L. and Samahita, M., 2020. What drives home solar PV uptake? Subsidies, peer effects and visibility in Sweden, En. Res. & Soc. Sci. 60. Available at: https://doi.org/10.1016/j.erss.2019.101319 [accessed 18.05.2021].

Munksgaard, J. Morthorst, P.E., 2008. Wind power in the Danish liberalised power market-policy measures, price impact and investor incentives, En. Pol. 36(10), 3940–3947.

OFGEM. 2017, Feed-in Tariff: Annual Report 2019, Available at: https://www.ofgem.gov.uk/system/files/docs/2017/12/feed-in_tariff_fit_annual_report_2016-17_0.pdf. [accessed 03.10.2021]

OFGEM, 2019. Smart Export Guarantee (SEG): Guidance for SEG Licensees- December 2019. Available at: https://www.ofgem.gov.uk/sites/default/files/docs/2019/12/guidance_for_seg_licensees_final.pdf [accessed 27.10.2021].

OFGEM, 2020 About Smart Export Guarantee. Available at: https://www.ofgem.gov.uk/environmental-and-social-schemes/smart-export-guarantee-seg [accessed 24.10.2021].

Solar Energy UK. 2021, Smart Export Guarantee League Table. Available at: https://solarenergyuk.org/resource/smart-export-guarantee/?cn-reloaded=1 [accessed 27.10.2021].

Zhang, M. M., Zhou, D. Q., Zhou, P. and Liu, G. Q., 2016. Optimal feed-in tariff for solar photovoltaic power generation in China: A real options analysis, En. Pol., 97, 181-192.