Techno-economic study on grid-connected PV system for major cities in Saudi Arabia

Amjad Ali[1], Muzafar Hussain[2], Fahad A. Al-Sulaiman[1,2], Shahbaz Tahir[3], Kashif Irshad[1], Md Hasan Zahir[1] and Muhammad Zeeshan Malik[4]

[1]Center of Research Excellence in Renewable Energy, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia.
[2]Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[3]Department of Electrical and Computer Science Engineering, Technical University Munich, Arcisstraße 21, München, Germany
[4]Faculty of Automation, Huaiyin Institute of Technology, Huai'an, 223003 Jiangsu, P.R China

Abstract. This paper presents the economic, technical, and environmental performance of a Grid-Connected PV System (GCPVS) designed for a residential building consisting of 14 families for six major cities of Saudi Arabia. HOMER Pro was used in this study for the evaluation of the techno-economical & environmental performance of the GCPVS. Neom, which a newly developed city on the west coast of Saudi Arabia, which has never been investigated before for such conditions, is also considered among the selected cities in the current study and thus makes the work novel. This analysis demonstrates that CO2 emissions are considerably higher as compared to their counterparts in both; grid alone and grid + PV systems. The studies concluded that the grid + PV system was feasible for all cities. Parameters like Net Present Cost (NPC), Cost of Energy (COE), and excess electricity were proportional to the PV penetration, but with the increase of PV penetration, CO2 emissions decreased. For the grid + PV system, Neom was found to be the most economical as it demonstrated the lowest NPC ($80,199) and CO2 emissions (63,664 kg/yr), among others. Neom, as a rapidly developing city in the North-West of Saudi Arabia, possesses great potential for PV. The results of this study can be used to study further PV systems in different climate zones of Saudi Arabia.

1 Introduction

During the last three decades, the construction industry, as well as the population of the Kingdom of Saudi Arabia, has increased drastically which has resulted in a marginal increase in the power consumption and demand. The power generation in the Kingdom of Saudi Arabia is totally from fossil fuels (Natural gas, Crude oil, Diesel, Heavy fuel oils) [1]. The power generation resources of Saudi Arabia are highly dependent on fossil fuels, which are a primary source of greenhouse emissions like CO_x, NO_x, SO_x, & PM, which are detrimental to the environment as well as human health. In line with the Kingdom's Vision 2030, the government of Saudi Arabia is looking for alternative green-resources of power generation such and has planned to produce 20 Gigawatt (GW) from PV, 7 GW from wind and 0.3 GW from other renewable sources like biomass, etc. by 2023 [2].

Many countries around the world are now taking grave measures to supplement conventional resources with the GCPVS. The benefits are not only limited to energy, but incentives are also provided to those who sell energy to the grid [3]. Some researchers have worked on the techno-economic feasibility analysis of GCPVS for different regions of the world. For example, Choi et al. [4] performed the economic analysis of GCPVS for a semiconductor facility in South Korea for different configurations considering (grid, PV, and battery) and their results showed that grid-only system was the least viable option among all other with decreased PV costs and increased grid costs. Al Garni et al. [5] studied the CGPVS for different tracking systems for Makkah and performed economic analysis using HOMER (Hybrid Optimization of Multiple Energy Resources). They reported that for Makkah, a vertical axis tracker with continuous adjustment depicted the lowest value of NPC and the highest COE. Adaramola

[6], using HOMER, studied the techno-economic viability of GCPVS for electricity generation for a location in northern Nigeria (Jos) and reported that the initial cost of the system plays a significant role in the electricity rate. Tomar & Tiwari [7] studied a GCPVS for a decentralized system in New Delhi and reported that the GCPVS without the storage-battery was economically viable for decentralized applications. Liu et al. [8] analyzed GCPVS for a residential building in Queensland, Australia, and found out that the PV system is an excellent way to reduce electricity bills and GHG emissions. GCPVS for fourteen different locations of Bangladesh were simulated by Mondal and Islam [9] using RETScreen. They reported that all sites had the potential for the GCPVS, and it could result in decreasing the GHG emissions by 1423 tonnes by employing the system at any location. Some challenges related to the power utilities, along with the contemporary position of GCPVS in the Pacific region, were elaborated by Raturi et al. [10], and they reported that any of the system: either stand-alone or GCPVS was economically viable and could counter the challenges faced. Kebedi [11], using HOMER along with RETScreen, studied the techno-economic feasibility of GCPVS for thirty-five different locations in Ethiopia considering 5 MW PV Plant on each site. It could generate 7658 MWh energy and had the potential for abatement of nearly 1089 tonnes of GHG emissions per annum.

It can be seen from the literature that a limited amount of consideration has been given to the roof-mounted GCPVS, especially for the region of Saudi Arabia. So, in this study, the techno-economic analysis of roof-mounted GCPVS installed in five different climate zones in Saudi Arabia [12] has been carried out. Six locations are selected for this study, one location for each of the five zones (Dhahran, Riyadh, Jeddah, Guriat, Khamis Mushait), as shown in Fig. 1 and an additional location Neom, a $500 billion city which is in the development phase in the North-Western part of Saudi Arabia, which has not been much studied till now to find out the potential of solar yield in that region. The aim of this study is to find out the best possible location for the proposed GCPVS. The study is for a residential building with fourteen families living in it and a GCPVS installed on the rooftop.

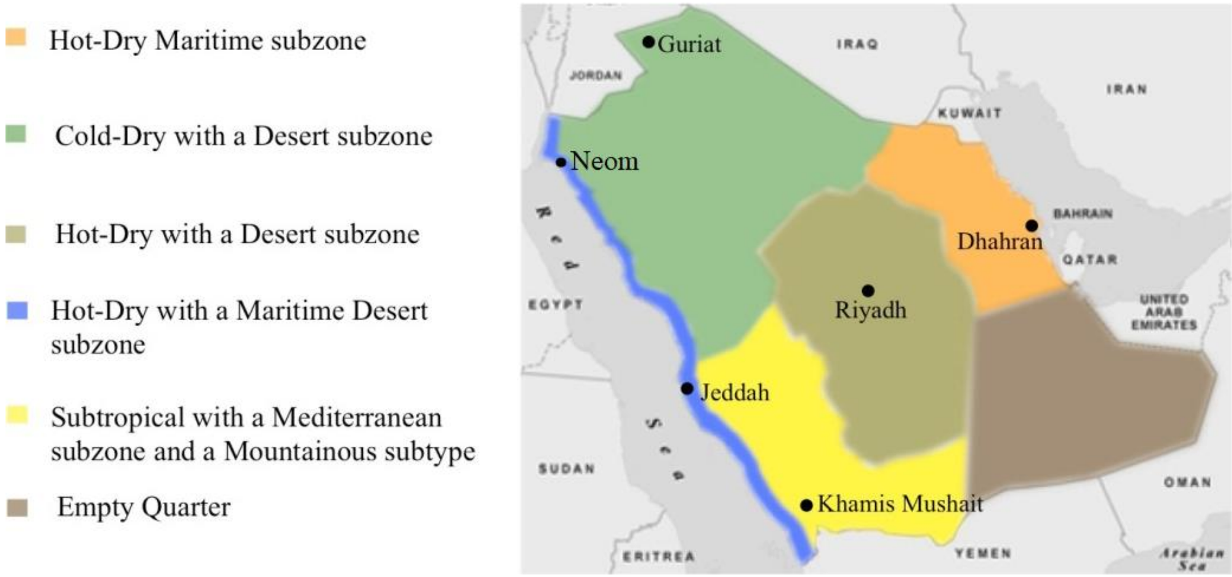

Fig. 1. Climate zones and selected locations for our study.

2 Methodology

2.1 Climatic information and the geographical regions

Solar irradiance and clearness index data in our study were obtained from NASA Surface Meteorology and Solar Energy database. The average global solar irradiance & clearness index (K_T) values scaled monthly for our geographical locations in the study are also represented by the following graphs. The clearness indices and monthly average solar radiation for all six locations are shown in Fig. 2 and Fig. 3 respectively.

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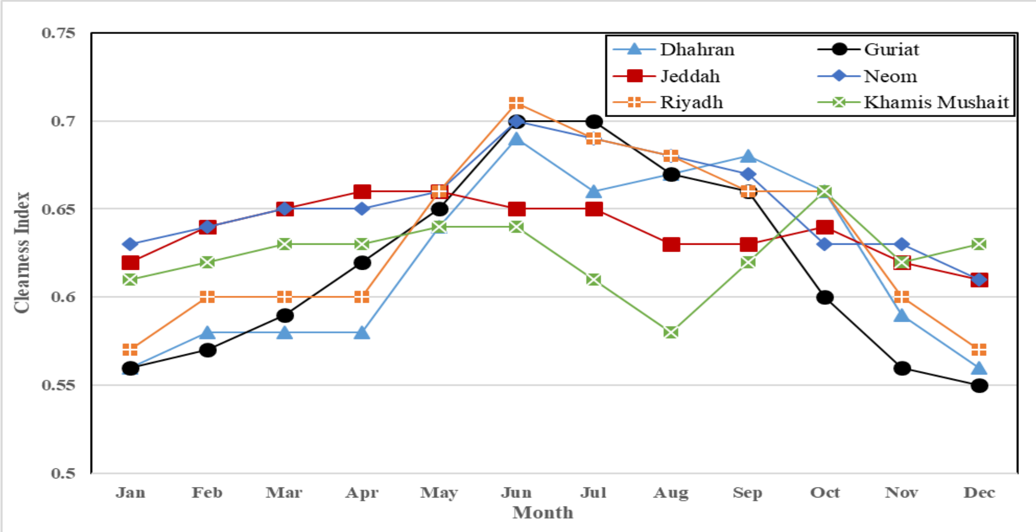


Fig. 2. Clearness index for selected locations.

2.2 Electric load data

One of the main scopes of our study was the scheming of the electrical load. Daily electrical load profile for 5 different climatic zones in Saudi Arabia with rooftop solar PV seven-storied building accommodating 14 households was fed in HOMER Pro. Common household devices were used in estimating the energy-consumption for all cases. Since this is a residential load, the least load demand was from 7 am to 4 pm evening, and the highest load required was 6 pm to 11 pm evening, and 6 am to 7 am in the morning. These load profiles were due to residential load as people mainly prepared themselves in the morning and left to their respective work locations, and in the evening, they all returned to their homes. The electrical load considered for the building is shown in Table 1.

The basis of the above assumption was the most recent statistical data from the Electricity Cogeneration and Regulatory Authority (ECRA) – Saudi Arabia, as illustrated in Fig. 4.

2.3 Grid and PV arrays description

Grid + PV configuration by its name indicates that a set of PV array is connected to the central grid. The entire assembly comprises of PV modules, charge regulator, converter, and load. Here PV arrays are the primary power source provider, and it must ensure uninterrupted power supply. In our study, a grid + PV is framed for application of roof solar photovoltaics building comprising of 14 households for different climatic zones in Saudi Arabia according to the meteorological and load data in the mentioned areas.

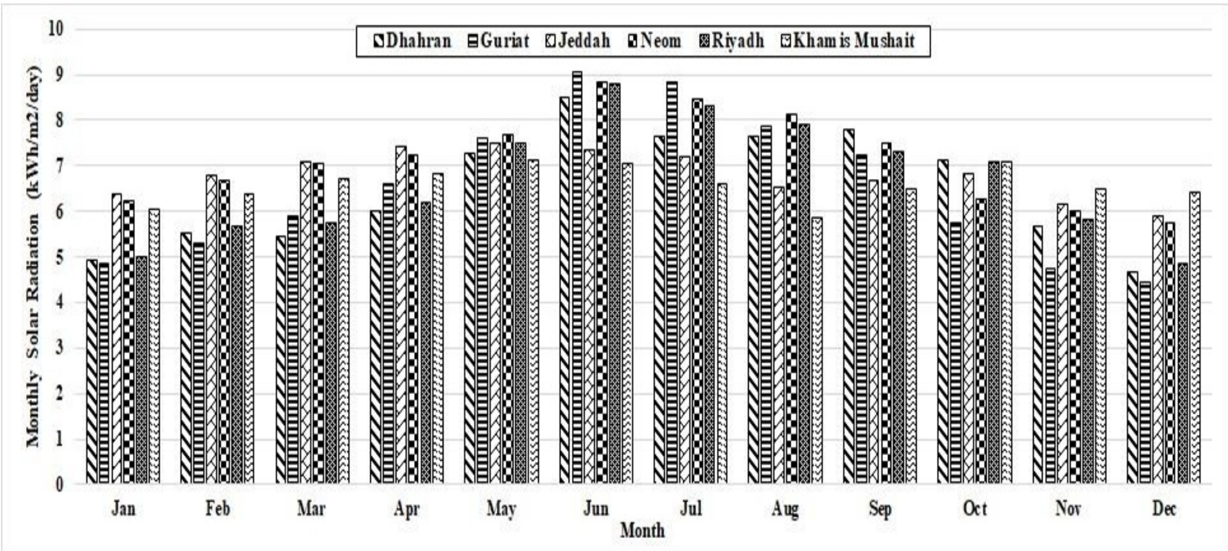


Fig. 3. Monthly solar radiation for selected locations.

Table 1. Electrical load calculation for a typical building.

City	Power	Units	Usage duration	Average daily consumption by single house	Average daily consumption of building
	(W)		(h/day)	(kWh/day)	(kWh/day)
Lighting	15/25/60	2/2/1	8	1.12	15.68
Television	150	1	3	0.45	6.3
Air heater	700	1	4	2.8	39.2
HVAC	1,100	1	7	7.7	107.8
Fridge	150	1	24	3.6	50.4
Laundry	300	1	1	0.3	4.2
Geyser	1500	1	2	3	42
Miscellaneous	100	1	24	2.4	33.6
Total consumption				21.34	300

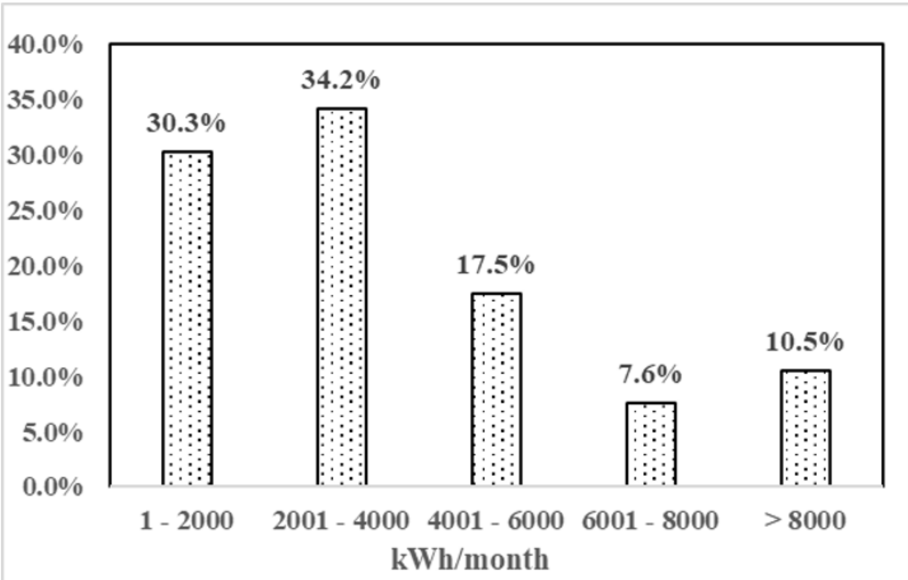


Fig. 4. Consumption of electrical units for the residential category in Saudi Arabia [1].

In our study, the Jinko Eagle PERC60 300W (Jinko60/300) mono-crystalline silicon (m-Si) PV modules were selected depending upon economical price and its rated efficiency. A derating factor of 0.88 is prescribed for this module. A horizontal axis daily adjustment type of tracking system is incorporated in our system. The efficiency of a PV module over a certain temperature limit starts decreasing with a further increase in temperature; thus, the effect of temperature coefficient is considered. The efficiency of this module rated is 18.3%. The initial capital and replacement cost of the module is \$1200/$kW_{p,}$ whereas the operating and maintenance cost is zero.

3 Results and discussion

3.1 Grid only system

This was our basic configuration as a reference in our analysis since it serves a major part of the electric load throughout the Kingdom. The optimized results of our study across all regions for grid only system are enlisted below in Table 2. With uniform electricity charges across the whole country, the COE was almost uniform. Here, in this type of configuration, there is neither capital nor replacement cost.

In terms of environmental aspects based upon emission in this system, Gurait and Khamis Mushait had higher emissions than the rest. From this, we may see as we rely on the grid, only system emissions in the form of CO_2 are considerably higher, causing a high contribution to greenhouse gases.

Table 2. Techno-economics of grid-only systems for different locations.

City	Grid	IC	NPC	OC	COE	Emissions (kg/yr)		
	(kW)	($)	($)	($/yr)	($)	CO_2	SO_2	NO_x
Dhahran	50	0	74,797	5,255	0.048	69,191	300	147
Riyadh	50	0	74,802	5,255	0.048	69,195	300	147
Jeddah	50	0	74,796	5,255	0.048	69,190	300	147
Gurait	200	0	74,811	5,256	0.048	69,204	300	147
Neom	50	0	74,806	5,256	0.048	69,200	300	147
Khamis Mushait	200	0	74,811	5,256	0.048	69,204	300	147

3.2 Grid + PV system

In these types of systems, the demand for electricity is met by the electricity produced by PV arrays and the grid. Here the irradiation and the temperature effect play a vital role in power production. From the feasible optimal results of this type of system enlisted below in Table 3 and Table 4, we observe that for Neom, the NPC and COE are least as this location also has a low operating cost resulting as the most economical city, among others, for this configuration. On the contrary, NPC and COE of Riyadh were the highest among the six cities. In terms of emissions, CO_2 emissions were highest in Riyadh, and the least was recorded for Neom from an environmental perspective in grid + PV configuration.

Table 3. Economic and environmental assessment of the optimal grid + PV system.

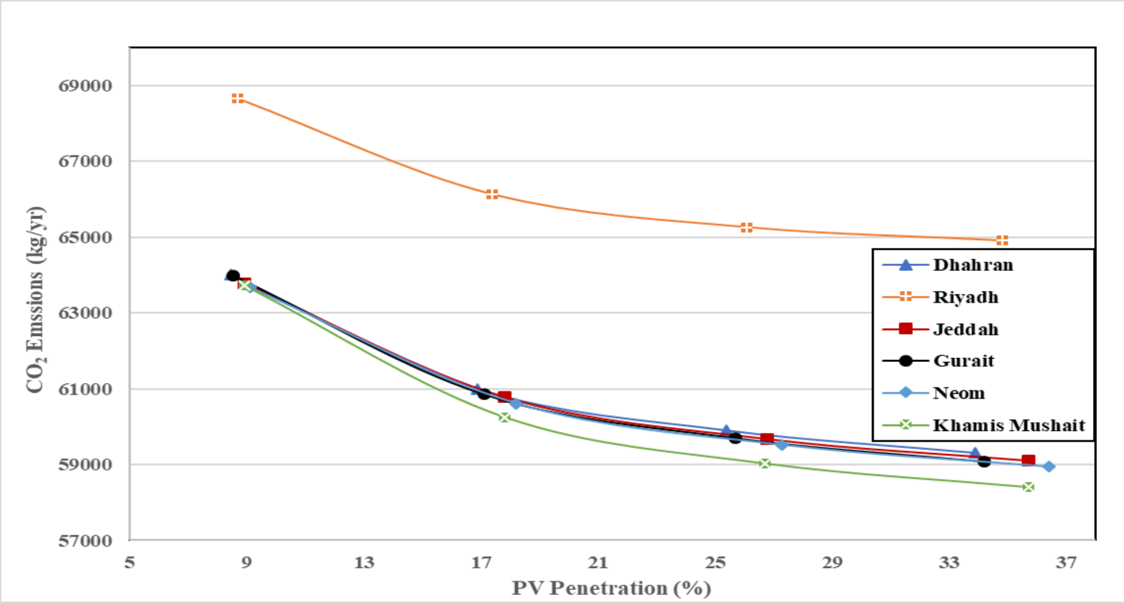
City	Grid	PV	IC	Converter	NPC	OC	COE	Percentage deviation in COE	RF	Emissions (kg/yr)		
	(kW)	(kW)	($)	(Units)	($)	($/yr)	($)	(%)	(%)	CO_2	SO_2	NO_x
Dhahran	50	5	10,000	5	80,599	4,960	0.0516	7.5	7.61	64,014	278	136
Riyadh	50	5	10,000	5	85,611	5,312	0.0548	14.1	8.06	68,664	298	146
Jeddah	50	5	10,000	5	80,323	4,941	0.0514	7.08	8.01	63,784	277	135
Gurait	200	5	10,000	5	80,556	4,957	0.0516	7.5	7.69	63,794	277	136
Neom	50	5	10,000	5	80,199	4,932	0.0514	7.08	8.18	63,664	276	135
Khamis Mushait	200	5	10,000	5	80,297	4,939	0.0515	7.29	8.02	63,719	276	135

Among the six locations in terms of annual generating minimum electricity obtained through the grid, purchases were for Khamis Mushait, which was 91% of the total energy produced, and the remaining maximum energy produced by PV was 9% of total energy generated. Whereas maximum annual generating capacity attained through grid purchases was for Riyadh which was 92% of total energy produced and the remaining minimum power generated by PV was 8% of total energy generated. Also, the percentage deviation in COE from the grid only systems is also calculated, which shows that the highest percentage deviation is highest for Riyadh.

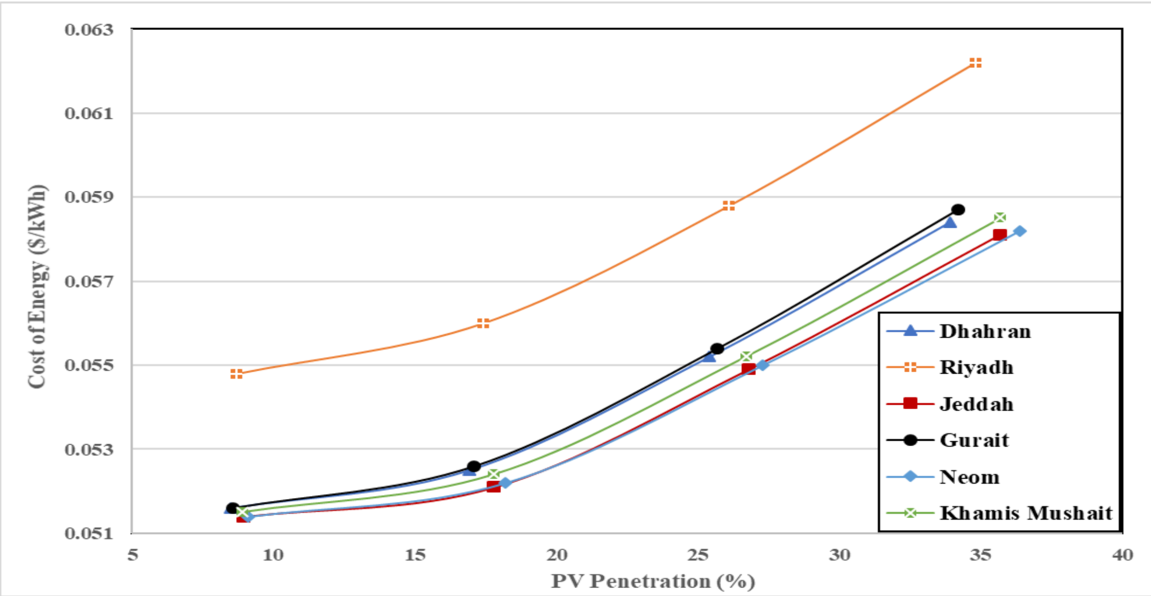
Table 4. Electrical production and consumption for optimal grid + PV system in six cities.

Capacity (kWh/yr)	Dhahran	Riyadh	Jeddah	Gurait	Neom	Khamis Mushait
PV Array Production	9,275	9,527	9,768	9,366	9,976	9,761
Grid Purchase	101,288	108,646	100,924	101,225	100,734	100,822
Total Production	110,563	118,173	110,691	110,591	110,710	110,583
AC Primary Load	109,479	109,487	109,481	109,500	109,493	109,500
Grid Sales	157	198	234	154	219	107
Total Consumption	109,635	109,685	109,715	109,654	109,712	109,607

The effect of PV penetration upon various factors such as CO_2 emissions and COE for grid + PV system of all locations of Dhahran, Riyadh, Jeddah, Gurait, Neom, and Khamis Mushait can be observed in Fig. 5. All configurations comprise inverter of 5 kW size and four PV array of sizes 5 kW, 10 kW, 15 kW, and 20 kW. We witness that as PV penetration increases, NPC and COE for grid + PV assemblies increases while the CO_2 emissions decrease for all the locations. The comparison studies of all cases for all locations indicates that system with 5kW of PV arrays, 5kW of inverter size at 9.1% PV penetration of Neom resulted in a healthy environmental and economic result with least NPC, COE, and CO_2 emissions.



(a)



(b)

Fig. 5. PV penetration impact on (a) CO_2 emissions and (b) cost of energy for six cities.

4 Conclusion

In our analysis, the pollutants were CO_2, SO_2, and NO_x in all systems considered. Moreover, CO_2 was the main constituent, and it should be the prime focus to mitigate CO_2 emissions.

In all cities, the lowest cost system was the grid only system, but it also emitted the highest amount of detrimental pollutants. On the contrary, the emissions from the grid + PV system were lower than the grid-only system, but it also rendered higher costs than the grid-only system. Thus, the grid + PV system is a good option as compared to its counterparts, but it is a trade-off in terms of emissions and economics.

For the grid + PV system, Neom was the most suitable location from an economic and environmental perspective with NPC of $80,199, COE of $0.0514 & CO_2 emissions of 63,664 kg/yr and PV penetration of 9.11% among all considered locations.

Acknowledgment

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