Development of techno-economic model for rooftop of solar PV in the LINE city of Saudi Arabia

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Abstract

A modernized and smart futuristic city of Kingdom of Saudi Arabia(KSA) named as 'the LINE' city will be constructed in the epic mountains of Tabuk region on the land called NEOM stretching to Red Sea. The city will be mirrored architectural masterpiece with an area of 500 x 200 m^2 and will operate entirely on renewable energy majorly solar energy. The planned rooftop of the LINE city will be covered with solar PV panels. In this research, a complete investigation of solar PV installation on the roof top was conducted by selecting three main regions of LINE city. Because the weather conditions are the main dominant factors on efficacy of the solar energy. The research starts with most up-to-date report on LINE city with all associated literature studies along with the KSA Vision 2030. In the next phase, rooftop of LINE city has been designed to cover with all solar PV panels. The observation was determined by considering both ends and a middle area of the city. Both theoretical and computational analysis were performed in terms of performance ratio, conversion efficiency, leveled cost of electricity and energy production. The comparative analysis of each case with other case studies were performed to finalized the most optimized solar PV installation region in the LINE city. Analysis of all components of solar PV systems, including arrays, inverters, connections, and storage are to determine the optimal system for meeting demand and assuring sustainability. The research helps to demonstrate the viability of solar PV installation on specific location of the city. The main objective of the research is to identify the most optimized location where the rooftop panels have the maximum energy production which helps the installation and other necessities on this particular location.

Keywords: LINE city, solar PV, installation, modeling, simulation, optimization.

Nomenclature:

Symbol	Definition
$E_{out,ac}(t)$	AC electrical energy output in year t (MWh)
$P_{in,dc}(t)$	DC power input in year t (MW)
$G(t)$	Average solar irradiance in year t (W/m²)
η_{inv}	Inverter efficiency (Percentage)
η_{sys}	Photovoltaic system efficiency (Percentage)
$CF_{dc}(t)$	DC capacity factor in year t (Percentage)
$H_{ann}(t)$	Annual sunshine hours (Hours)
$EY(t)$	Energy yield in year t (kWh/kWp)
$PR(t)$	Performance ratio in year t (-)
$E_{dis,bat}$	Battery discharge energy (kWh)
$E_{ch,bat}$	Battery charge energy (kWh)
$REff_{bat}$	Battery efficiency (Percentage)
$E_{gen}(t)$	Electrical energy generation in year t (MWh)
$BEC(t)$	Battery energy conversion rate in year t (-)
$C_{ann}(t)$	Annual costs in year t (USD)
δ	Annual discount rate (Percentage)
$LCOE_{ann}$	Annual levelized cost of energy (USD/kWh)
ω	Inflation rate (Percentage)
$LCOE_{real}$	Real levelized cost of energy (USD/kWh)
$E_{cons}(t)$	Energy consumption in year t (MWh)
$Tariff(t)$	Electricity tariff in year t (USD/kWh)
$EB_{ns}(t)$	Electricity bill without solar in year t (USD)

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$EB_{ws}(t)$	Electricity bill with solar in year t (USD)
$NS(t)$	Net savings in year t (USD)
$NS(t)$	Net present value of the investment (USD)
IC	Initial cost of the system (USD)
$NS_{t,ann}$	Annual savings in year t (USD)
SPB	Simple payback period (Years)
i	Interest rate (Percentage)
DPB	Discounted payback period (Years)
IRF	Incentives and tax rebate amount (USD)
NCC	Net capital cost of the system (USD)

1. Introduction

Over the past few decades, the Kingdom of Saudi Arabia (KSA), one of the biggest producers of fossil fuels worldwide, has experienced exponential expansion [1-4]. This growth has led to increased energy demand, necessitating a larger portion of its oil production to satisfy domestic energy needs. Additionally, the widespread use of fossil fuels has contributed to a rise in air pollution globally, which in turn has accelerated the process of global warming [5-7]. Saudi Arabia has launched a plan called Vision 2030. It aims to gradually replace oil-based energy with renewable energy sources [8, 9], as well as the establishment of contemporary cities controlled totally by artificial intelligence and dependent on sustainable energy sources, such as NEOM and its subprojects, including the LINE city [10-14]. It is anticipated that renewable energy will contribute 9500 MW of energy by 2023, and solar power will contribute greatly to this goal [15, 16].

As part of this revolutionary development, KSA Vision 2030 unveils ambitious plans for the Saudi government to improve its economy with several projects that go beyond the use of fossil fuels and create a new society dependent on renewable energy, enabling the country to move from an oil-dependent economy to a knowledge-based economy [17–19]. In the topographically varied province of Tabuk, on the west coast of the Red Sea, the Saudi Arabian government inaugurated a new city in 2017 (shown in Figure. 1) [14]. It is a smart city with smart technology and a comprehensive tourism destination. The city will serve as both a smart city technology platform and a tourism destination. Only sustainable energy sources will be used in this city. Due to the volatility and unpredictability of the two renewable energy sources, a hybrid renewable energy system combining both wind power and solar energy is recommended [20, 21].

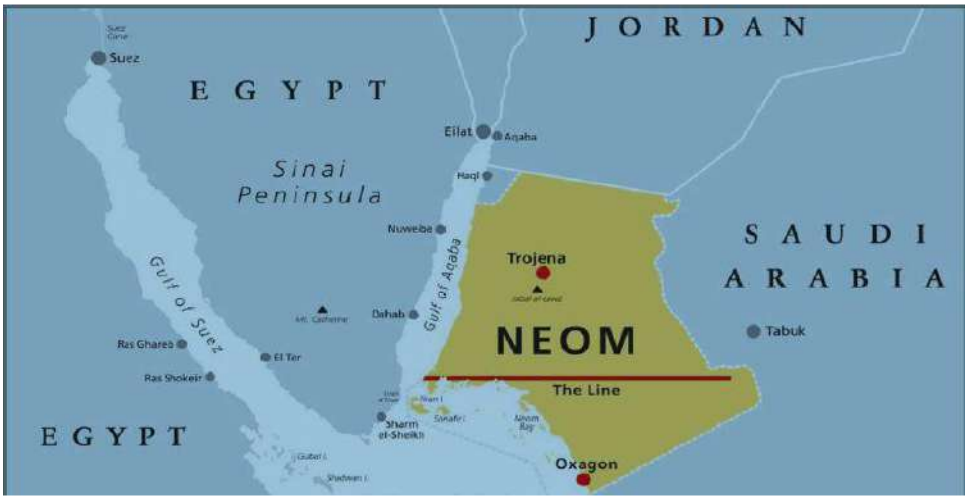

Figure 1. Location of NEOM and its sub-projects (the LINE city) along with other surrounding countries [14]

2. The LINE city:

The Saudi government announced in 2021 that its impressive project, called city of the LINE which will be constructed in NEOM [22]. Using artificial intelligence to strengthen the environment, it will explore a unique urban living experience along a 170-kilometer stretch of land that will be zero carbon emissions, free of noise, and be without automobiles [13]. This unprecedented announcement has changed all known concepts of the design of the urban city. It is indeed the city of the future. It is planned to be a technology, which is based completely on local sustainable energy sources, known as Net-Zero Energy Buildings (NZEB) [13, 23, 24]. To achieve all of that, it is clear that using solar photovoltaic systems in this spanned structure is ideal to meet the possible demand for energy in the facility. A typical solar PV project can be divided into five stages; (1) planning, (2) engineering, (3) construction, (4) operation, (5) decommissioning. It is critical to do a life-cycle analysis for the PV systems so that the designer, as well as the construction manager, can take their decision based on the benefit-cost ratio and consider durability as the main goal for the project [25].
Over the past few years, many studies have been conducted in Saudi Arabia as well as across the globe to assess and predict the behavior of renewable energy sources and their potential to serve as replacements for the current energy source [26-32]. Recent studies underscore the significant shifts in Saudi Arabia's energy consumption patterns from non-renewable sources, driven by robust economic growth and extensive social development, with detailed analyses and policy implications discussed in the referenced literature as illustrated in Figure 2 [33, 34]. The population reached up to 27 million, from 4 million since 1960 [35]. As a result, the KSA is the largest consumer of electricity in the GCC in 2016, with 345 TWh of gross consumption. Nearly 59% (205 TWh) of the energy is generated by natural gas, while 41% (140 TWh) is derived through oil [36].

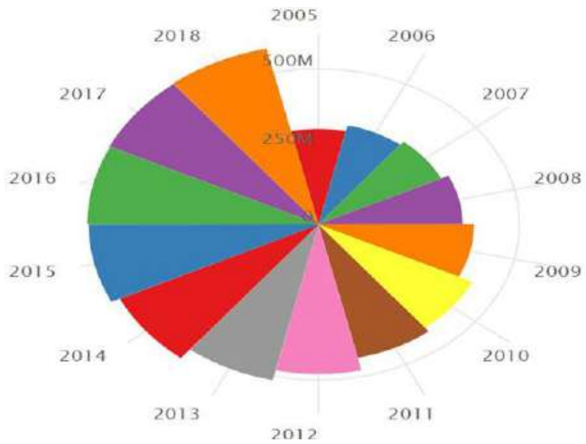

Figure 2. Total of KSA electricity consumption between 2005 and 2018 by MWh [33, 34]

Residential energy consumption increased until it reached half of the total energy produced. As an alternative energy source, rooftop photovoltaic power generation can be used to reduce NEOMs dependence on the national grid. The study by Alqahtani and Balta-Ozkan [37] explores the integration of rooftop photovoltaic systems with battery storage in NEOM's residential sectors, finding optimal system sizes and orientations to effectively reduce dependency on the national grid and support Saudi Vision 2030's sustainability goals. It computed the Levelized Cost of Energy, the Net Present Cost, the Orientation of PV Panels, and the Optimum PV System Size, concluding that the PV system required varies depending on the type of residential facility (villa, traditional dwelling, apartment), as illustrated in Figure 3.

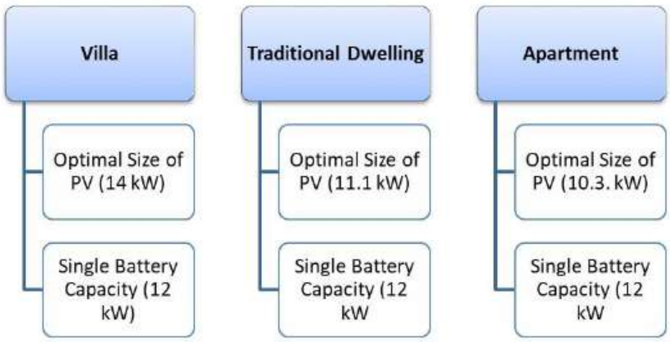

Figure 3. PV System to Be Used in Residential Facilities [37]

Boretti and Castelletto [20] reported on how artificial intelligence can be used to cover the demand for energy in NEOM city through the use of renewable energy. Sources such as thermal solar systems, photovoltaic solar systems, and wind systems have many advantages as well as defects, as shown in Figure 4 [21]. The study concluded that composing these three systems together would be the ideal solution to overcome the inadequacies of each system.

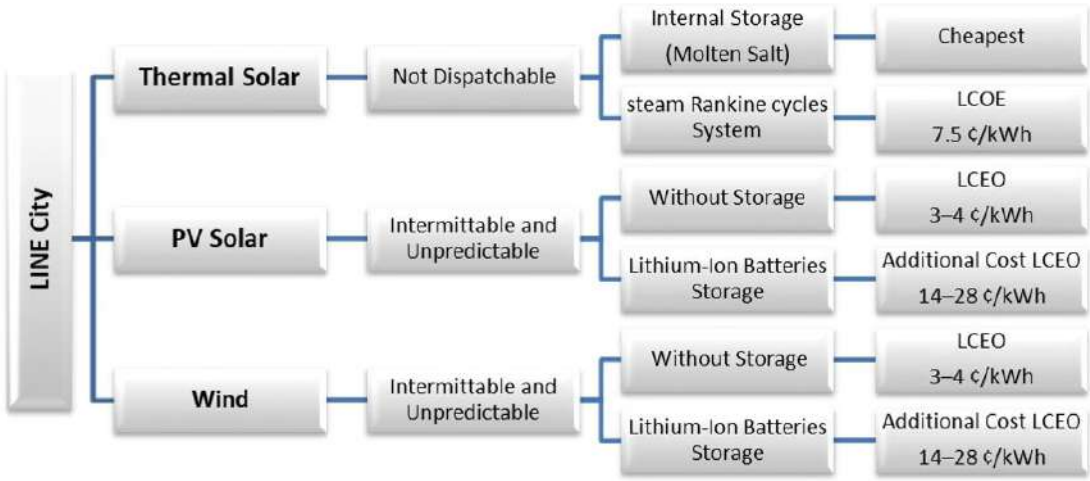

Figure 4. Table illustrates properties of all renewable systems, which are suggested to be used in the LINE city [21]

A study by Khan et al. [1] assesses the potential for rooftop photovoltaic systems in the residential sector of the Kingdom of Saudi Arabia, taking into account the proper design of solar systems and the local architectural and cultural features of homes. Projected to commence energy generation in 13 major cities, the study concludes that these installations could collectively produce at least 51 TWh of energy, equivalent to 30% of the total domestic demand in KSA [1]. Grab Boretti [21] discusses the main elements regarding the mitigation of risk and business management decision-making. It also explains the main threats facing plans for the implementation of the cyber city project NEOM in KSA including any surrounding external risks related to the project. The study identified the challenges in the management of the projects. The challenges include the possibility of insecurity regarding funding, the need to implement a prototype taking into consideration the early stage of most technological advancements to be featured, and the requirement for properly moderating and managing the changing and civilization process in Saudi Arabia [37]. Nkuriyingoma et al. [38] outline the problems that developing countries face huge difficulties regarding the continuity of electricity, especially in rural areas. This problem can be solved according to the author through the integration of BESS-supported renewable energy sources into the grid. Including the possible agriculture activities of the households, the study concluded that the annual energy requirement is 82.34 MWh with a peak load of 30.4 kW. According to the simulation, a PV system with an installed capacity of 57.33 kWp and a BESS of 89.2 kWh storage capacity can supply the load with its power consumption of 68.65%, a level of self-sufficiency of 64.38%, and a performance ratio of 86.05% when the desired ratio is set to 110% with a year as the reference period and an amortization period of 9.65 years. These results demonstrate that the integrated system of the BESS-PV solar system is a positive investment in developing countries [38]. Paszkowska-Kaczmarek [11] investigates both the geometry and the legitimacy of the city of the LINE. The author sparked a discussion about this city and its ability to fulfill and achieve contemporary and future urban needs. The study included information about urban cities that used linear geometry in their design and attempted to implement the design over 150 years [11]. Al-Sayed et al. [13] describe the goal of any smart city to conserve the surrounding natural resources. The study also concluded that the city of the LINE is considered a city of zero carbon dioxide emissions, it relies entirely on renewable sources of energy generation. the researchers highlighted the difficulties and challenges accompanied by technological developments for sensors and data collection in the city of the LINE. These developments will help us to reach any destination in the city in only a few minutes [13]. It is possible to appreciate the difficulties and challenges of implementing the project by comparing the enormous energy requirements to operate and facilitate this enormous skyscraper that extends over 100 miles with the enormous predictable energy requirements. Solar photovoltaic systems will be put under tremendous pressure due to the type of activities inside as well as the transportation system requirements. Also, we should identify the capacity of storage for the energy being produced by the solar photovoltaic systems to maximize the reduction in demand from the grid [37].

In the current study, most up-to-date literature about current activities and scenario of both NEOM and LINE city is presented. Among various highly concentrated locations of the LINE city, three most suitable locations are selected for optimal and maximum energy production. Theoretical and computational modeling is performed by considering various parameters such as PV systems installation, arrays, inverters, connections, storage, levelized cost and energy and to meet the demand and to assure sustainability. The research is extended to optimized the selected locations according to the required conditions and finally comparative analysis of all cases are conducted to finalized the most optimized location.

3. Research Methodology:

The futuristic city stretches 170 km long with a height of 500 meters above sea level. The meteorological conditions across the LINE is different as one side is close to the Sea while the other side in the desert. This makes use of the understanding that various energy parameters may have different values and outcomes throughout the long stretch boundary. Since, the entire city will run completely on clean energy sources therefore, it is important to consider all the contingent conditions and parameters. This will help to finalize the more optimized clean energy solution. The current research is focused on the techno-economic analysis of solar PV installation in the LINE city. Three cases have been selected as shown in figure.5 based on the metrological conditions and other corresponding parameters as it is directly related to the efficiency performance of the PV system installations at the top of the city.

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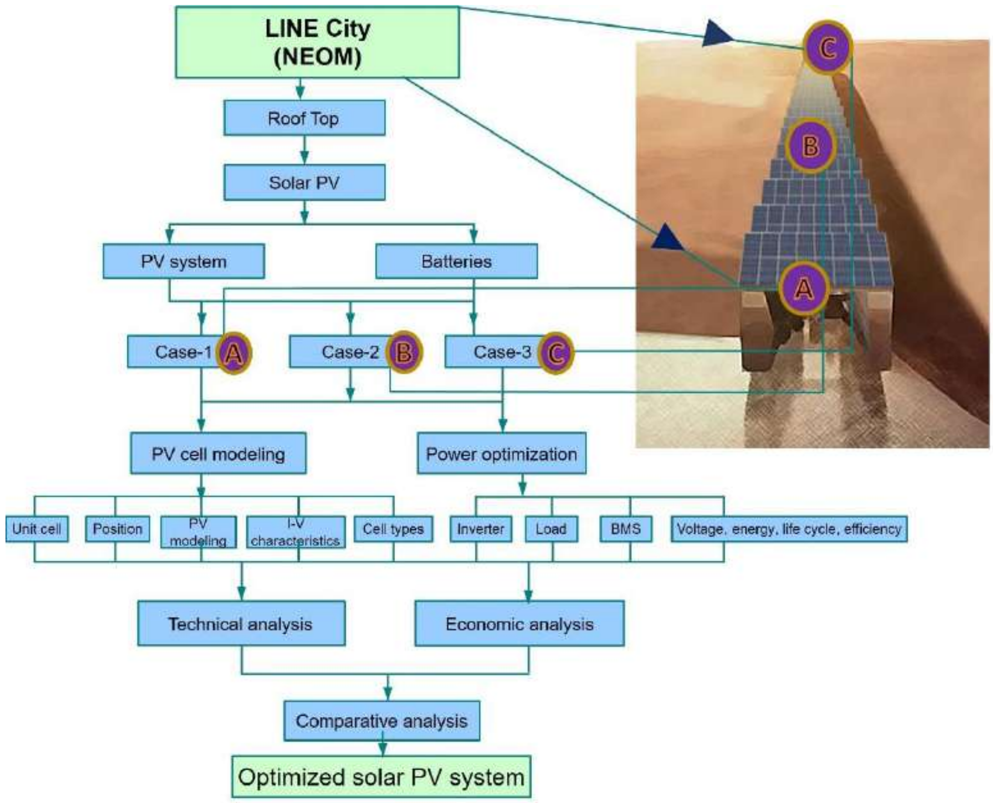

Figure.5 Schematic diagram of LINE city covering with PV panels on rooftop

We structured the research according to the following cases as follows,

3.1 Case-1(close to the Sea)
3.2 Case-2(mid of the LINE city)
3.3 Case-3(close to the desert)

3.1 Case-1(close to the Sea)

In this case, we consider the sea edge of the LINE city as the starting point that will have fleet of ships for tourism as well as for business purposes. It is deemed to plant more than 200 species of the rare habitant around this edge of the city.

3.2 Case-2(mid of the LINE city)

The city stretches a long way of 170 km and as discussed, there might be variation across many regions of the city. Therefore, in this case, we consider the mid of the LINE city and conduct both technical and economic analysis of solar PV installation across the roof top.

3.3 Case-3(close to the desert)

This case is selected as the end of the LINE city and the beauty of this edge is that, it lies in the deep desert phase. Therefore, it is important to discuss about the efficiency of the solar PV installation at the roof top compared to other section of the city.

4 Theoretical analysis:

In this study, a comprehensive set of equations is employed to analyze the performance and financial feasibility of solar energy systems. The annual AC electrical energy output$\left(\mathrm{E_{out,ac}(t)}\right)$ is calculated using equation (1),

$$E_{out,ac}(t) = \sum\left(P_{in,dc}(t) \cdot G(t) \cdot \eta_{inv} \cdot \eta_{sys}\right) \quad (1)$$

while the DC capacity factor $\left(\mathrm{CF_{dc}(t)}\right)$ is determined for each year through equation (2),

$$CF_{dc}(t) = \frac{E_{out,ac}(t)}{\left(P_{in,dc}(t) \cdot H_{ann}(t)\right)} \cdot 100 \quad (2)$$

To assess the system's efficiency, the energy yield $\left(\mathrm{EY(t)}\right)$ is computed with equation (3),

$$EY(t) = \frac{E_{out,ac}(t)}{P_{in,dc}} \quad (3)$$

Moreover, equation (4) is utilized to derive the performance ratio $\left(\mathrm{PR(t)}\right)$, another crucial performance indicator.

$$PR(t) = \frac{E_{out,ac}(t)}{\left(P_{in,dc} \cdot G(t) \cdot H_{ann}(t)\right)} \quad (4)$$

The battery efficiency $(\mathrm{REff_{bat}})$ and battery energy conversion rate $(\mathrm{BEC(t)})$ are calculated using equations (5) and (6), providing valuable insights into the energy storage aspect of the solar system.

$$REff_{bat} = \frac{E_{dis,bat}}{E_{ch,bat}} \cdot 100 \quad (5)$$

$$BEC(t) = \frac{E_{ch,bat}}{E_{gen}(t)} \cdot 100 \quad (6)$$

To appraise the financial dimensions of the solar system investment, equation (7) is employed for the annual levelized cost of energy $(\mathrm{LCOE_{ann}})$ calculation, and equation (8) is used for the real levelized cost of energy $(\mathrm{LCOE_{real}})$ computation.

$$LCOE_{ann} = \frac{\sum\left(C_{ann}(t)\cdot(1+\delta)^{-t}\right)}{\sum\left(E_{ann}(t)\cdot(1+\delta)^{-t}\right)} \quad (7)$$

$$LCOE_{real} = \frac{LCOE_{ann}}{(1+\omega)^{-t}} \quad (8)$$

The electricity bill without solar $\left(\mathrm{EB_{ns}(t)}\right)$ and net savings $\left(\mathrm{NS(t)}\right)$ are estimated through equations (9) and (10), respectively. The net present value (NPV) of the investment, a vital financial metric, is determined using equation (11).

$$EB_{ns}(t) = E_{cons}(t)\cdot Tariff(t) \quad (9)$$

$$NS(t) = EB_{ns}(t) - EB_{ws}(t) \quad (10)$$

$$NPV = \sum\left(\left(NS(t) - C_{ann}(t)\right)\cdot(1+i)^{-t}\right) \quad (11)$$

Lastly, the simple payback period (SPB) and discounted payback period (DPB) are estimated using equations (12) and (13), respectively. Equation (14) is employed to compute the net capital cost (NCC) of the system after considering incentives and tax rebates.

$$SPB = \frac{IC}{NS_{t,ann}} \quad (12)$$

$$DPB = \sum\left(\frac{NS(t)}{(1+i)^{-t}}\right) \quad (13)$$

$$NCC = IC - IRF \quad (14)$$

By applying these equations, the solar system's performance and financial feasibility can be thoroughly analyzed, thereby facilitating well-informed decisions regarding solar energy technology and its investments.

5 Computational analysis:

National renewable energy laboratory (NREL) in USA developed a robust and efficient simulation program named as System Advisor Model (SAM) which helps in designing many renewable energy systems. Conducting feasibility analysis of solar PV system including both commercial and residential projects are of prime importance. Therefore, in the current research, SAM has been used to simulate all the three cases mentioned above. The simulation model consisted of site selection as the initial input parameters so as to exactly determine the feasibility assessment of PV system. The program works on the principle of monticarlo method and performance model based on MATLAB language which is then exported to Excel sheet as presented in figure.6.

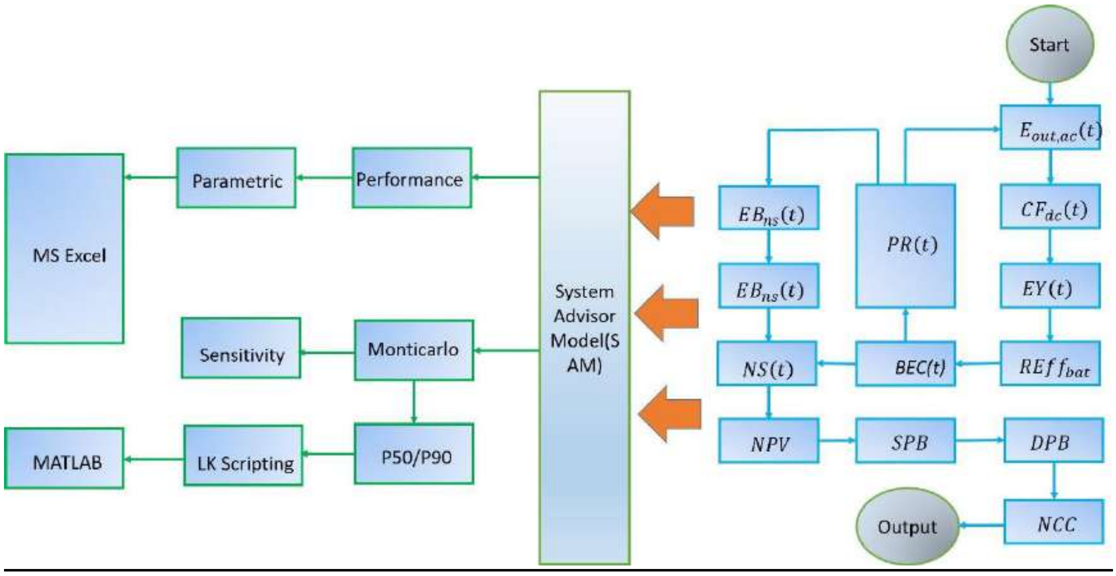

Figure.6 Flow diagram of theoretical and simulation model

6 Results and discussion:

The study was conducted by performing techno-economic analysis of installation of solar PV system at the roof top of the LINE city. The investigation consisted majorly about energy production and cost estimation scenarios of each case separately as well as between all the three cases as presented in table.1.

Table.1 Case studies and comparative analsysis

Metric	**Case studies**			**Comparative analysis**		
	1(A)	2(B)	3(C)	1 vs. 2	1 vs. 3	2 vs. 3
Annual AC Energy in Year 1 (kWh)	4,403,336.1	4,486,479.3	4,602,03.5	1.9%	4.5%	2.6%
DC Capacity Factor in Year 1 (%)	8.8	8.9	9.2	1.1%	4.5%	3.4%
Energy Yield in Year 1 (kWh/kW)	769	784	804	1.9%	4.5%	2.6%
Performance Ratio in Year 1	0.32	0.32	0.31	0.0%	3.1%	-3.1%
Battery Roundtrip Efficiency (%)	0.17	0.12	0.12	-29.4%	29.4%	0.0%
LCOE Levelized Cost of Energy Nominal (¢/kWh)	17.24	16.92	16.50	-1.9%	4.3%	-2.5%
LCOE Levelized Cost of Energy Real (¢/kWh)	13.33	13.08	12.76	-1.9%	4.3%	-2.5%
Electricity Bill Without System (Year 1) ($)	163,446	163,446	163,446	0.0%	0.0%	0.0%

Electricity Bill With System (Year 1) ($)	113,254	118,967	113,254	5.0%	0.0%	-5.0%
Net Savings With System (Year 1) ($)	50,192	44,479	50,192	-11.4%	0.0%	12.9%
Net Present Value ($)	9262120 0.9	9262320. 5	926252 1.20	-0.0%	0.0%	0.0%
Net Capital Cost ($)	9933932. 35	9933293. 3	993239 33.5	0.0%	0.0%	0.0%
Equity ($)	993393.3 5	993393.3	993393 3.5	0.0%	0.0%	0.0%
Debt ($)	0	0	0	0.0%	0.0%	0.0%

Comparative analysis of the three cases presented in table.1 dictates that the maximum efficiency is concluded when case-1 was studies against case-3. The annul energy production at the coastal side of LINE city was calculated to be 4403MWh while 46032 MWh was observed at the desert end of LINE city. The comparison of the energy yield has been calculated to be 4.5%. Similarly, the same observation of energy production between the middle of LINE city and both ends were calculated which appeared to be 1.9%(A to B) and 2.6%(B to C) respectively. Since, the rated yield was found to be high which implies that the corresponding maximum energy efficacy to be in the middle of the LINE city. The battery roundup efficiency is 29% which is quite high for this case as well. The further, the levelized cost of electricity(LCOE) was found to be 16.50 cents/kWh which is the cheapest value among the rest of the cases.

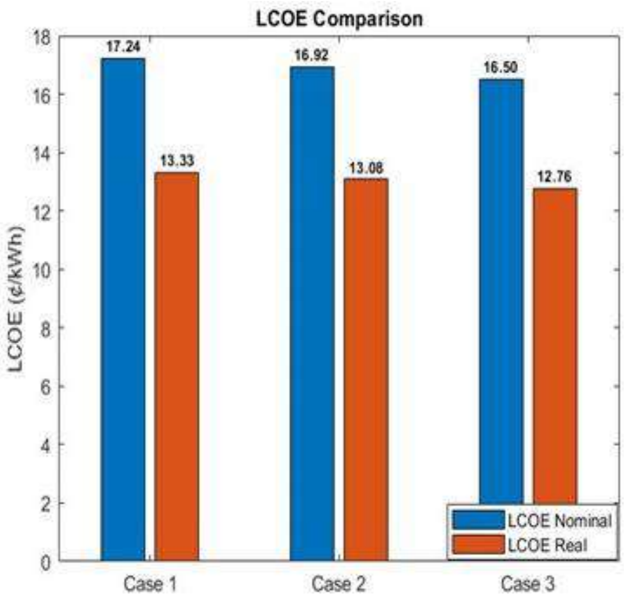

Figure.7 levelized cost of electricity for all cases

In figure.7 it can be observed that the nominal Levelized cost of electricity attained the highest values in case-1 as compared to case-2 and case-3. Similarly, the real values of LCOE in all the cases received highest values in case-2. The observation dictates that levelized cost is highest near the coastal edge of LINE city while it has minimum values at the desert end of the city.

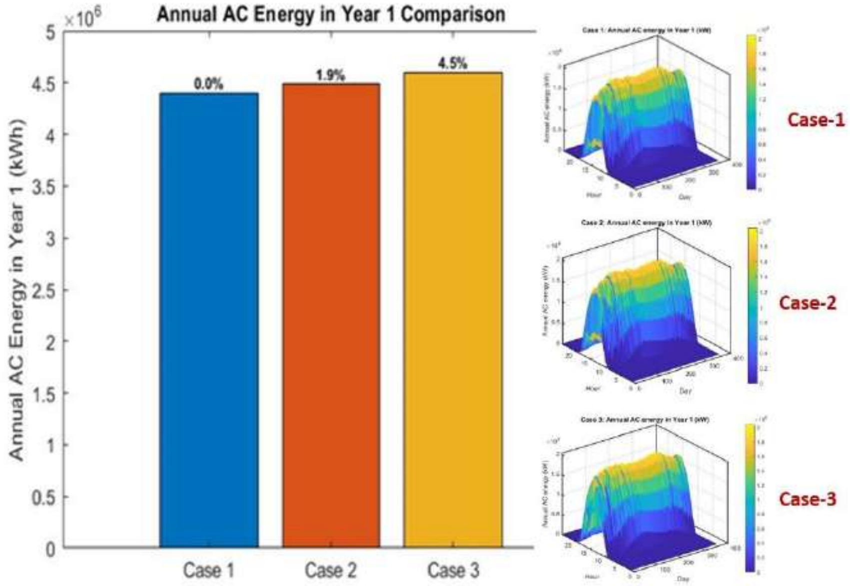

Figure.8 Trends of annual energy with 3D graphs of day/hours for all cases

The calculation shows that energy yield is higher in case-3 therefore, the LCOE values need to be lowest at this side of LINE city. The illustration of figure.7 is very well depicted in figure.8, thus confirming the accuracy of results obtained in table.1 as well. In figure.8, it is observed that annual AC energy is maximum in case-3 which has been deduced already.

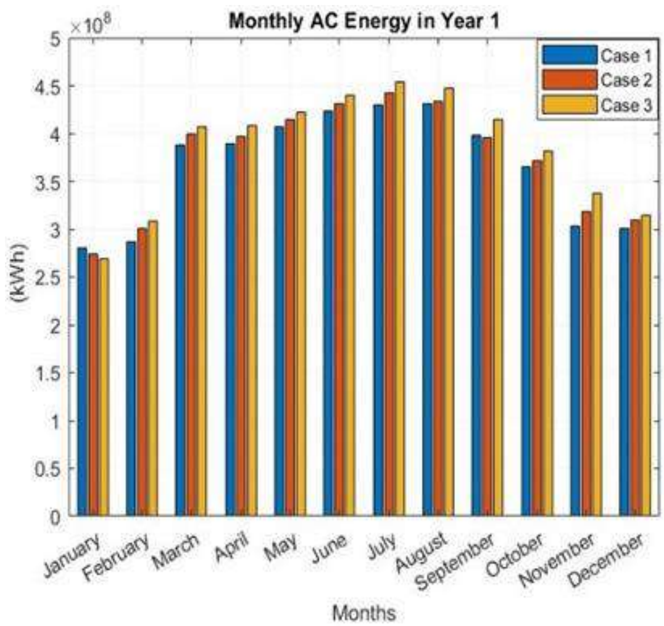

Figure. 9 Trends of monthly energy production (for one year)

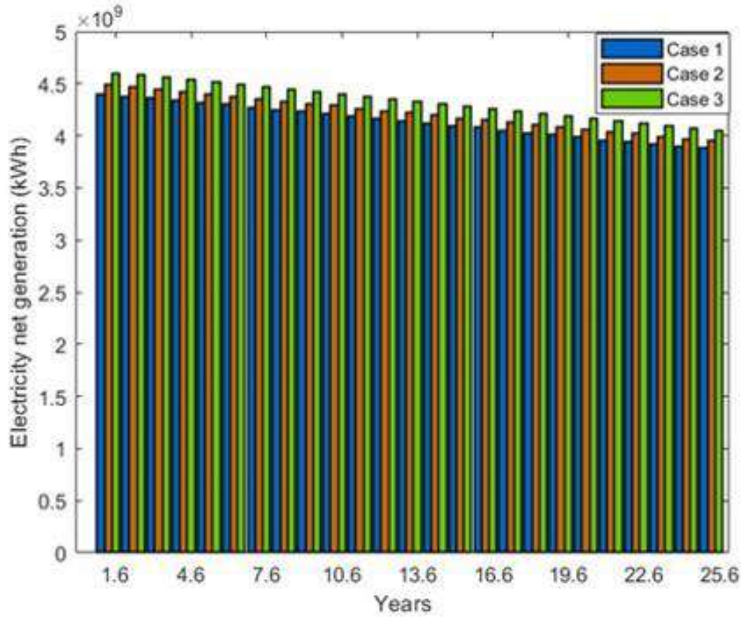

Figure 10 Trends of electricity generation (25 years)

The month wise energy production profile is necessary and to get the feasibility of installation of PV panels therefore, in this research, monthly AC energy is calculated for a year to see the highest peak profile of sun intensity. It can be observed in figure.9 that maximum energy yield is calculated in the month of July while the lowest in the January. However, for the reported cases, it can be seen that the maximum AC energy is obtained in case-3 in the month of July followed by case-2 and then case-3. This simply indicates that AC values decreases toward case-1(coastal side of LINE city). Contrary to this, a reverse trend of securing maximum AC values was obtained in Case-1 followed by case-2&3 in similar pattern. This happened due to the sunrays strikes partially in the Tabuk region during winter season and also desert region of LINE city would be affected by the less humidity level as compared to coastal region of LINE city that permits higher radiation affects. For the practical implication of the LINE city electrical generation through solar PV for 25 years. It can be observed in figure.11 that maximum electricity generation was obtained in case-3 in all the years and record a homogenized pattern. While, case 2 and case-3 attained lower values. The trend confirms the calculated energy yield of 4.5% and LOCE values which are mentioned in figure.10 and figure.9 respectively.

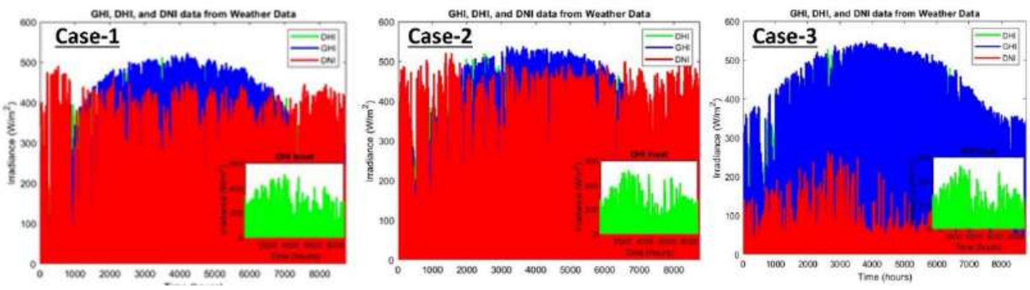

Figure.11 Radiation pattern of cases

Some of the important parameters that affect the performance of PV include, Diffuse Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI) and Direct Normal Irradiance (DNI) which are illustrated in figure.11 for all the cases. It has been observed that case-3 has the lowest DNI and GHI values is much higher which dictates that weather profiling linked to the radiation pattern varied according to the particular places of the LINE city. For all the three cases, it has been observed that the case-2 appears to have the highest DNI and lowest DHI which implies that PV panels can receive the highest intensity while avoiding other factors. However, simulation results are more supported to case-3 while considering all the facts and figures of the reported PV installation in LINE city.

The irradiance pattern throughout the LINE city as per the reported cases (1-3) is shown in figure.12. All the diffusive losses and shading effects were calculated through hourly time step and azimuthal angle of the sun. The investigation was performed for shading, soiling and reflection. It can be observed that case-3 received the highest reflection values as compared to rest of the cases. The pattern shown in figre.8 includes the soiling due to dust and accumulation in the panels or other main components such as connecting wires, AC/DC loses, tracking, module mismatching and transformer losses.

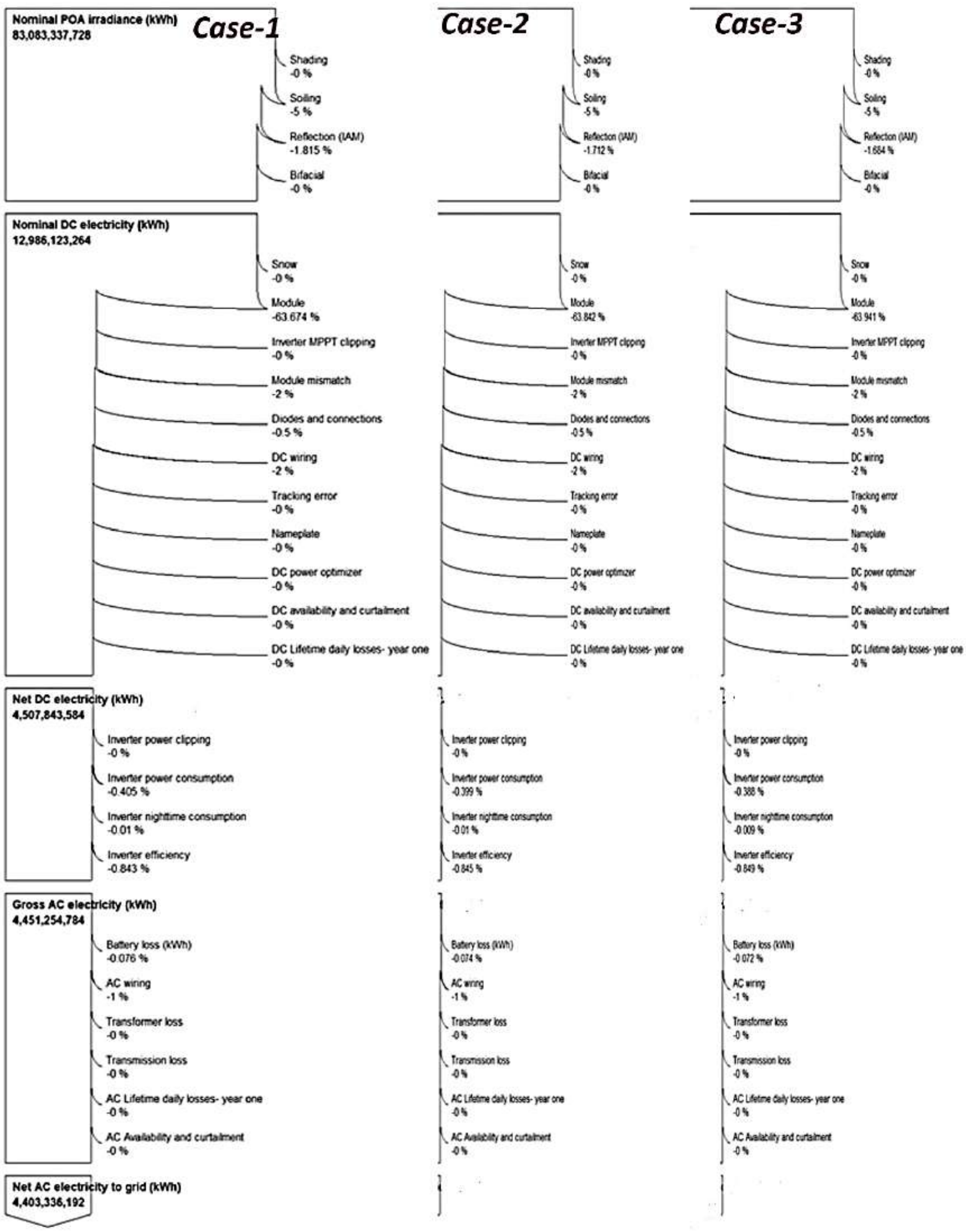

Figure.12 Energy loss trends for all cases

7 <u>Conclusion:</u>

The current research concluded the installation of solar PV installation in the LINE city which is a towered type, highly modern building which is deemed to be called as 'future of urban living' in the Kingdom of Saudi Arabia. It has been observed that out of three locations of the LINE city, the most optimized solar installation location was concluded to be the in the desert edge of the city. The annual energy production was calculated as 46,032 MWh which is 4.5% higher in comparison with other location points. Further, the cost of electricity production was observed to be 16.50 cents/KWh which is acceptable as per the running cost of PV installations across the globe. The net capital cost was calculated to be 9.3 Million $ which is lower than other cases. The study suggests the optimized installation of solar PV panels on the specific location of the LINE city. This research helps the decision makers and associated partners to figure out the techno-economic assessment of solar PV across the LINE city.

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9 Conflict of interest

All authors declare no conflict of interest.

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