Development of a Single Graphical User Interface Platform-based Solar PV System Model for Effective PV Component Sizing

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ABSTRACT
The deployment of solar energy system is necessary to meet the energy demands of the rural areas in Nigeria. The investment for the system components is capital intensive and therefore, a techno-economic model which can be used to rapidly design the system is imperative. This paper presents the development of a novel and unique solar PV energy system model (SPVSM) which can be used to accurately size PV system components. It also has energy and economic analysis panels all on a single GUI platform. As a case study, the model was applied to a rural area in Maiduguri, Nigeria. Energy demand of 1.1MWh per day, mean hourly irradiance of 266 W/m2 and mean daily sunshine hours of 7.89 hours which were obtained for a 10-year data of the location were used. The model was applied to accurately size the solar PV components and performed the energy and economic analysis to ascertain its viability. From the energy analysis panel, an annual output of 409.2 MWh was obtained from the system. As for the economic analysis, the capital cost was $2.394 million and considering a system lifespan of 25 years, the Net Present Value (NPV) of the project and the LCOE are $657.96 million and $0.0812/kWh respectively. From the simulation, 2226 number of 300 W module are required. The model developed is quite simple to adapt. The use of solar energy for power supply is highly desirable because it is a source of energy that is inexhaustible, environmentally friendly and economically viable.

Keywords: Solar photovoltaic energy, economic analysis, LCOE, irradiance

Introduction

The increase in world's population and technological development has undoubtedly led to rapid increase in global energy demand. The most widely used resource for electrical energy generation are the fossil fuels but studies have shown that these resources have negative environmental and health impacts [1]. This has led to the growing interest in the use of renewable energy sources such as solar photovoltaic for power supply.

Nigeria has inadequate supply of energy to both urban and rural areas with about 60% of its population in the rural areas having no access to energy security which is "the uninterrupted availability of energy at an affordable price" [2]. Lack of energy security is one of the major causes of poverty in the rural areas of Nigeria as this is associated to the bad economic and social impacts of either lack of adequate energy, or exorbitant prices that are not competitive or are very unstable [3]. The demand for electricity in Nigeria obviously outweighs the supply, this inadequate supply is further bedevilled with frequent outages and consequently low reliability as a result of inadequate power infrastructure, poor grid network and poor maintenance culture. A large percentage of Nigerians rely on petrol or diesel generators for power supply for both domestic and industrial usage. Nigeria is endowed with verse energy resources such as oil, gas, hydro and solar resource. Figure 1 shows Nigeria's solar radiation map.

The availability of solar energy on the earth depends on the geographical location, time and season. The area under study is indicated on the map by Zone I for Maiduguri. The thick circle close to Maiduguri indicates the location of study which is in the North-Eastern Nigeria. Osueke, Uzendu and Ugbonna [5] studied the variation in solar irradiance in 4 different sites in Nigeria using data acquired from National Aeronautics and Space Administration (NASA) Research and employing SPSS statistical tool and a bar chart. The study concluded among other things that Maiduguri laying at latitude 11.9° and longitude 13.1° seemed to experience highest solar irradiance, which ranges from 5.5 – 6.7 kWh/m^2/day, this translates to 229.2 – 279.2 W/m^2.

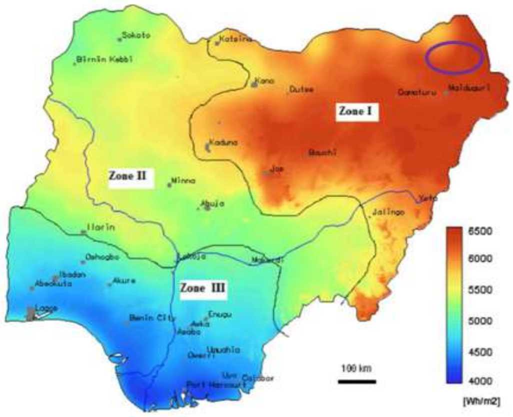

Figure 1: Nigeria's Solar Radiation [4]

The utilization of solar energy to economically meet the ever-increasing energy demand of the world relies on two important aspects: the panel generation factor of the site which is a function of solar irradiance availability and the necessary technology to harness it. To be able to assess the performance of solar energy conversion systems in a location, it is imperative to be aware of the level of solar energy availability at the location. It is clear from Figure 1 that Nigeria is favoured with the availability of solar energy and North-Eastern Nigeria, which is the area under study, is one of the regions most favoured in terms of solar energy availability. Figure 2 shows a typical village in the North-Eastern Nigeria that is not connected to the National grid and has no form of electricity supply and has high solar irradiance which makes solar PV viable.

HOMER (Hybrid Optimisation Model for Electric Renewables) is a micropower computer optimization model that simplifies the task of designing hybrid renewable micro-grids. It has capability for design of off-grid and grid-connected systems. HOMER finds the least cost combination of components that meet electrical and thermal loads. It simulates thousands of system configurations, optimizes for lifecycle cost, and generates results of sensitivity analyses on most inputs [6].

SAM (System Advisory Model) is a computer model that calculates and simulates the performance and financial metrics of renewable energy systems such as photovoltaic, concentrating solar power, solar water heating, wind, geothermal, biomass, and conventional power systems. Its advanced simulation options has the capability for parametric, sensitivity and statistical analyses using Monte Carlo simulation and weather variability studies [7]. Past versions of SAM over the years do not have the capability for sizing solar photovoltaic system component until the latest version was released in 2020 with capability to size betteries [8]. Sizing of other components are yet to be included in SAM.

PVsyst is a PC software package for the study, sizing and data analysis of complete PV systems. This software handles grid-connected, stand-alone, pumping and DC-grid (public

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transportation) PV systems, and includes extensive meteo and PV systems components databases, as well as general solar energy tools. This software is geared to the needs of architects, engineers, researchers. It is also very helpful for educational training. The latest version, PVsyst 7.0, which was released on 25 May 2020 has in its release notes, new features which include economic evaluation such as Levelized Cost of Energy (LCOE), Net Present Value (NPV), multiple loans of multiple types, advanced depreciation configuration economic evaluation now available for Stand-alone and Pumping systems in this latest version.

Figure 1 shows how greatly endowed Nigeria is with solar energy resource and Figure 2 shows how lowly powered the rural communities of Nigeria is. This is to stress the need to invest in solar PV technology for power supply in Nigeria.

The investment for large solar PV power plants is capital intensive, therefore, a solar photovoltaic system model (SPVSM) which can be rapidly used for accurate sizing of the system components for optimized solar PV system for power supply becomes imperative.

Figure 2: Gora Village in North-Eastern Nigeria (Photo by the Researcher during the initial field work)

I. Development of Solar PV System Model on a Single GUI

A. Description of the Model

SPVSM was developed for accurate sizing of solar PV system components (PV array, battery, inverter, and charge controller) and conducting energy and economic analysis of the system. The package has the capability for conducting a sensitivity analysis on the energy and economics of the system considering variation in degradation factor and discount rate. It also gives an economic appraisal such as net present value (NPV) over the expected lifespan of the project. It is built on a single GUI platform but with six executable panels each handling different aspects of component design, energy and economic analysis.

A. Executable Panel 1 - PV array Sizing

Energy demand, E_D is an important parameter required in sizing solar PV array. The peak watt of solar PV module required for any energy demand depends on the Panel Generation Factor (PGF) of the location. Some of the model equations used for the sizing are given in equations 1 and 2. Figure 3 shows the Executable Panel 1. The PGF can be calculated from equation 1.

$$PGF = \frac{Solar\ irradiance\ of\ site \times sunshine\ hours}{Standard\ test\ condition\ irradiance} \quad (1)$$

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Designing for 30% higher energy gives equation 2.

$$E_{ARRAY} = E_D \times 1.3 \qquad (2)$$

The peak watt W_p, of the solar PV array is given by equation 3:

$$W_p = \frac{E_{ARRAY}}{PGF} \qquad (3)$$

For any module rating M_R, the number of modules M_N which is adequate to meet the energy demand is given by equation 4.

$$M_N = \frac{W_p}{M_R} \qquad (4)$$

A. Executable Panel 2 - Battery Sizing

Two key parameters that guides the accurate sizing of a battery bank is the energy demand and number of days of autonomy, N_D. Figure 4 shows the executable GUI panel for battery sizing. It should be noted that the energy demand has been declared in the PV module sizing panel.
The battery bank total capacity (Amp.hour) is given by equation 5.

$$Battery\ bank\ capacity = \frac{E_D \times N_D}{V \times DOD} \qquad (5)$$

Where V is battery voltage, DOD- depth of discharge and N_D – number of days of autonomy
F or a selected battery of amp hour, AH, the total number of batteries required to meet the energy demand is given by equation 6.

$$Number\ of\ batteries = \frac{E_D \times N_D}{V \times DOD \times AH} \qquad (6)$$

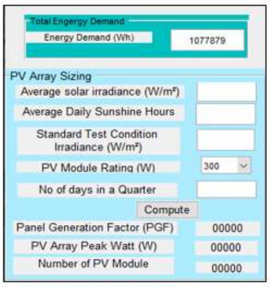

Figure 3: Photovoltaic Module Sizing Executable GUI panel

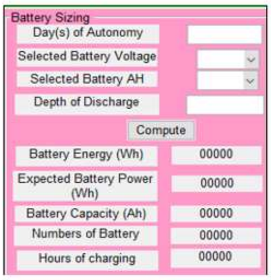

Figure 4: Battery Sizing Executable GUI panel

B. Executable Panel 3 - Inverter Sizing

Usually the inverter is sized 25-30% [9] higher than total wattage demand.. Figure 5 shows the executable GUI panel for inverter sizing. For a load of wattage W_L, the total wattage of inverter required is given by equation 7.

$$W_{T\_INV} = W_L \times 1.3 \qquad (7)$$

the number of inverters to meet the required power for a selected inverter wattage of W_{INV} is given by equation 8.

$$\text{Number of inverters, } N_{INV} = \frac{W_{T\_INV}}{W_{INV}} \qquad (8)$$

C. Executable panel 4 - Charge controller sizing

Figure 6 shows the charge controller sizing GUI executable panel.
The parameters necessary for sizing charge controller are the peak watt of the solar array and the system voltage S_v. Charge controllers are rated in amperes. The total charge controller capacity is given by equation 9.

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$$Total\ Charge\ controller\ capacity,\ T_{CC} = \frac{W_P}{S_V} \qquad (9)$$

For any chosen charge controller unit with capacity, CC_C, the total number of such charge controllers that are required is given by equation 10.

$$No\ of\ CC, N_{CC} = \frac{T_{CC}}{CC_C} \qquad (10)$$

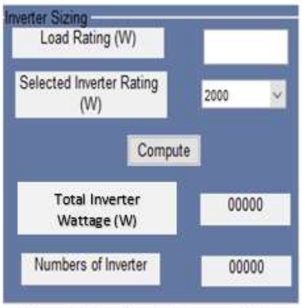

Figure 5: Inverter sizing executable GUI module

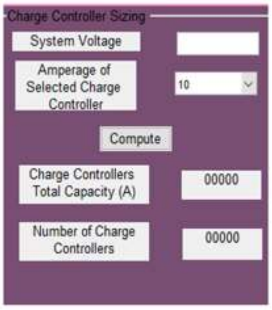

Figure 6: Charge controller sizing executable GUI module

D. Executable panel 5 - Energy analysis

The energy from a PV array depends on the peak watt of the array (W_p), conversion efficiency, the daily sunshine hours (SSH) and the average solar irradiance (ASI) of the site. The energy produced by the array per annum can be obtained from equation 11, where STCI is standard test condition irradiance which is 1000 W/m^2. The annual energy over the lifespan of the system is calculated using equation 12. Figure 7 shows the energy analysis panel.

$$E_A = W_P \times \frac{ASI}{STCI} \times SSH \times PV_{Derate} * Efficiency * 365 \qquad (11)$$

$$E_A = W_P \times \frac{ASI}{STCI} \times SSH \times DF * Efficiency * 365 * (1 - DEG_A * YR) \qquad (12)$$

E. Executable panel 6 - Economic Analysis

The economics of the system was developed bearing in mind the market price of components and some economic assumptions. The economic appraisal methodology employed to assess this proposed PV system is the NPV viz; discount rate of 5%, approach. This gives the present worth of the project by calculating the cash tariff of \$0.12, equity of 30% of TPC and loan of 70% of TPC. Where TPC is total project cost. The discount factor, D_F can be obtained from equation 13, where r and YR represents the discount rate and year respectively.

$$D_F = \frac{1}{(1+r)^{YR}} \qquad (13)$$

The capital cost can be calculated using equation 14.

$$C_C = PVM_C + INV_C + CC_C + B_C + Ass_C \quad (14)$$

Where PVM_c, INV_c, CC_c, B_c, Ass_c represent costs associated with the PV array, inverters, charge controllers, batteries and other associated costs respectively. Figure 8 shows the economic analysis panel.

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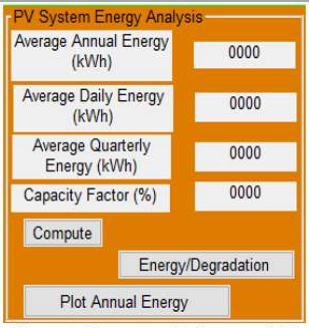

Figure 7: Energy analysis executable GUI panel

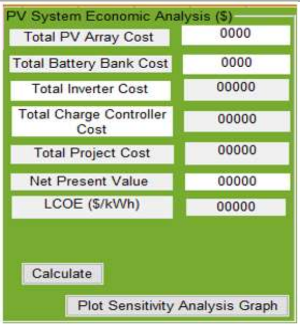

Figure 8: Economic analysis executable GUI panel

Results and Discussion

After developing the SPVSM GUI, it was subjected to a case study in Maiduguri with energy requirement of about 1.1 MW/day. Figure 9 shows the result of the simulation for each of the six panels on a single GUI platform. Most solar photovoltaic systems which are above 500kW are usually grid-tied but the villages in North-eastern Nigeria being considered in this study are very far from the National grid. In some instances, more than 100 km apart. This distance combined with the frequent power outages makes PV grid-tied system economically and technically unviable for this region. Most software does not handle large solar farms as standalone which is one unique thing about this model (SPVSM).

Solar PV component sizing

Considering the energy demand of 1,077.879 kWh/day and all the other inputs such as irradiance and sunshine hours as it relates to Maiduguri, Figure 9 shows the output of the six panels on a single GUI platform. It displays the accurate sizing of modules, batteries, charge controller and inverter. It also presents the energy and economic analysis. Table 1 shows the sizes of the components.

Table 1: Parameters of solar PV components

	PV Module	Battery	Inverter kW	Charge Controller
Rating per unit	300 W	6V 1200AH	8 kW	80 A
Total No. Reqd.	2225.530 ~ 2226	598.8 ~ 600	20.7	173.86
Total	667.6kW	4.3 MWh	165.6	13909 A

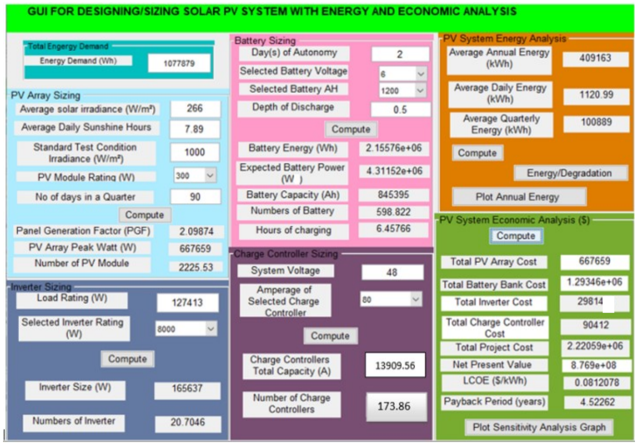

Figure 9: Solar PV System model on a single GUI

F. Energy and Economic Analysis

Figure 10 and Figure11 show the energy and economic analysis of the system. The energy panel shows the average annual, daily and quarterly energy generated by the PV array. The panel also has the capability to present graphical representation of the annual energy generated over the lifespan of the plant taking into account the degradation effect. This is presented in Figure 12. The average annual energy generated by a 667.7 kW power plant is 409,163 kWh. Figure 11 shows the cost implications for the designed solar PV system to supply about 1,077.9 kWh of energy per day to a village in the North-eastern Nigeria. The total costs of all major components are presented in Figure 11. The net present value of the plant for estimated lifespan of 25 years is $876.9 million. The levelized cost of energy as shown in the economic panel is $0.0812/kWh. This is in line with the 2019 report of International Renewable Energy Agency. IRENA [10] stated that solar PV projects commissioned in 2018 had a global-weighted-average LCOE of $0.085/kWh. This LCOE according to IRENA [10] is around 13% lower than the equivalent figure for 2017 and that the value has fallen by 77% between 2010 and 2018.

Figure 12 shows the annual energy generated over the lifespan of the plant at varying degradation rates. In the model, a degradation of 1% per annum was assumed, this is in tune with available PV system degradation rates found in literature. Zweibel and Herch (2018), Charaf, *et al.* (2021), Bernard *et al.* (2021) stated that annual degradation rate for solar panel is between 0.5% to 1%. There are two phases, the construction/installation phase and the operation phase. During the construction phase as can be seen in Figure 10, the energy generated is zero obviously. The highest energy output was obtained during the first year of operation as there is least degradation. The energy generated during the fifth year of operation is 402,800 kWh for a degradation of 0.5% and 392,500 kWh for a degradation rate of 1%, this is about a 2.5% drop in energy generated. For the purpose of analysis, PV energy generated was simulated with varying degradation rates. The energy generated during the 25th year of operation for a degradation rate of 1% is 3.099×10^5 kWh which is 16.6% higher than energy generated for a degradation rate of 1.5% during the same year.

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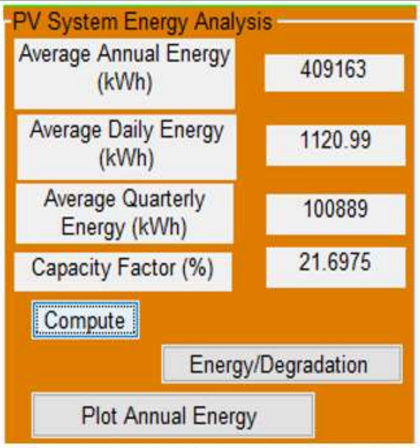

Figure 10: Energy analysis executable GUI panel

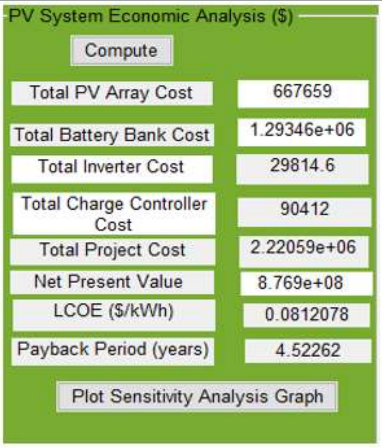

Figure 11: Economic analysis executable GUI panel

Figure 13 shows the graph of annual present value against the year of operation with the sensitivity analysis based on varying discount rates. The sensitivity analysis shows that the annual present value of the system increases from the year of commission to the 17th year of operation and then it begins to decline for discount rate of 5% while decline begins at year 7 of operation for discount rate of 10% During the 1st year of operation, the NPV for a discount rate of 5% is $1.048 million while $0.7285 million for 15% discount factor which gives a 30.5% reduction in NPV. It can be noted there is a downward trend of the annual present value during the construction/installation years, this is because during these years, the cash inflow is obviously zero and therefore the present value which a discounted difference cash inflow and outflow over the lifespan of the plant is negative.

The result obtained with the developed model using the case study are in good agreement with those obtained using PVsyst and HOMER.

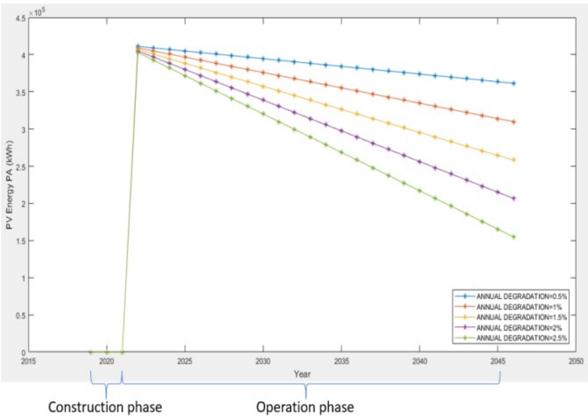

Figure 12: Annual energy over lifespan of project at varying degradation rate

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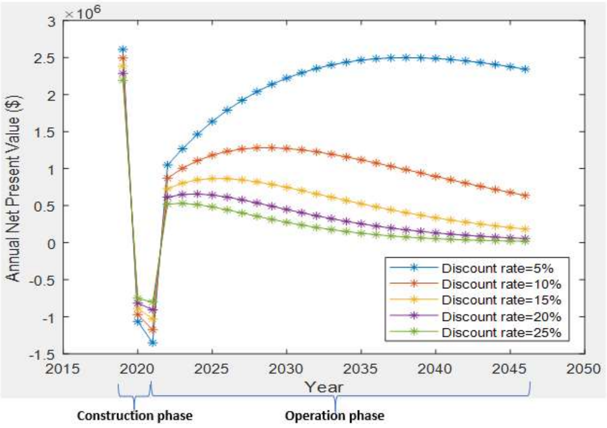

Figure 13: Annual present value over years of operation

CONCLUSION

A solar PV energy system model has been developed. The model which was developed on a single graphical user interface has the capability to accurately size solar PV system components and conduct energy and economic analysis. The model was subjected to a case study in Maiduguri, North-eastern Nigeria. With the knowledge of the required parameters of the site and the energy requirement. The model gave a 2226 number of 300-watt module, 600 number of batteries with rating of 6V and 1200 AH, 21 number of 8000-watt inverter and 174 number of 80 A charge controller. The energy and economic analyses show that the development of solar PV system for power supply in the area under study is economically viable.

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References

[1] Ö. Ayvazoğluyüksel and Ü. B. Filik, "Estimation methods of global solar radiation, cell temperature and solar power forecasting: A review and case study in Eskişehir," *Renew. Sustain. Energy Rev.*, vol. 91, no. May 2017, pp. 639–653, 2018, doi: 10.1016/j.rser.2018.03.084.

[2] IEA, "Global Energy & CO2 Status Report: The latest trends in energy and emissions in 2018," 2019. [Online]. Available: https://www.iea.org/geco/electricity/

[3] IEA, "What is Energy Security," *International Energy Agency*, 2019. https://www.iea.org/topics/energysecurity/whatisenergysecurity/

[4] A. Giwa, A. Alabi, A. Yusuf, and T. Olukan, "A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria," *Renew. Sustain. Energy Rev.*, vol. 69, pp. 620–641, 2016.

[5] C. Osueke, P. Uzendu, and I. Ogbonna, "Study and Evaluation of Solar Energy Variation in Nigeria," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 3, no. 6, p. 5, 2013.

[6] NREL, "Homer," *Nationaal Renewable Energy Laboratory*, 2014. https://www.nrel.gov/docs/fy04osti/35406.pdf (accessed Sep. 20, 2020).

[7] N. Blair *et al.*, "System Advisor Model, SAM 2014.1.14: General Description," Oak Ridge, 2014. [Online]. Available: www.nrel.gov/publications.

[8] NREL, "System Advisor Model (SAM) Release Notes," 2020. https://nrel.github.io/SAM/doc/releasenotes.html (accessed Sep. 19, 2020).

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[9] M. Chandel, G. D. Agrawal, S. Mathur, and A. Mathur, “Techno-economic analysis of solar photovoltaic power plant for garment zone of Jaipur city,” *Case Stud. Therm. Eng.*, vol. 2, pp. 1–7, 2014, doi: 10.1016/j.csite.2013.10.002.

[10] IRENA, “RENEWABLE POWER GENERATION COSTS IN 2018,” Abu Dhabi, 2019. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf