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Technical and Economic Assessment of PV Resource Based DC and AC Connected Behind the Meter System for Residential Load

Khan Huma Aftab[1], Mohd. Yusuf Yaseen[2], Mohammed Asim[3]

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Abstract: Electric-energy storage using the behind-the-meter system is presently considered as a beneficial scheme of providing renewable energy to the grid. Presently mandates are introduced and subsidies are proposed for adoption of such systems in various countries. In this work solar photovoltaics (PV) array with behind the-meter storage is taken under consideration and presenting an analysis of the benefit of systems installed by customer in Lucknow, U.P, India. Variety of dispatch strategies, including automated peak-shaving & manual scheduling are investigated for determining the best mode to use for the system of energy storage that helps in increasing the value of system and mitigating the demand charges. Recent ongoing electric tariffs, and site-specific load and weather database are integrated for performing a accurate analysis by utilizing the open access, publicly available tool known as System Advisor Model (SAM). It has been found that installation of PV structures with a lithium-ion battery system capable to yields positive net-present values with consideration of high demand charge utility rate structures and dispatching the batteries utilization under day-ahead forecasting. Conclusions about influential factors to determine the net present value considered that shows high sensitivity of economics of battery to the combination with system parameters at specific location.

Keywords: *Energy prediction, Rooftop crsytalline solar cells, Solar Photovoltaic, Solar radiation*

1. Introduction

Development in energy & power industry related to generation, transmission & distribution process are important to meet the high energy demand of customer. For achieving a reliable & efficient power generation, transmission and distribution highly complex calculation are to be performed. At present, most of the power generating stations in India using the fossil fuels, it is leading to low security, economic & environmental issues [1]. Apart from power generation units, there are several issues of reliability, and losses connected to transmission & distribution networks. These network of transmission & distribution system is very complex in many locations especially in hills, towns, and cities with no proper planning and future scope of availability of electrical energy . For overcoming such issues related to present energy & power sector to meet the load demands, distributed generating system running with renewable energy sources may be planned to adopt [2, 3].

An alternative to the fossil fuels is renewable energy resources effectively opting for generation power in an efficient mode because of the ecofriendly nature [4]. These renewable resources of energy installed in location having power supply uncertainties and backup is provided for meeting out high load during certain period of time. Among different types of resources of renewable energy, solar power has used widely for generation of power in maximum part of tropical regions especially in India [5]. Here, solar energy selected under as analysis in terms of performance & feasibility at specific locations in India with respect to recorded weather data, requirement of load, configuration of installation, tilt angle, PV module and different electrical components used. The selection of Photo Voltaic process as a source of electricity generation covers multiple constraints for capturing the stock of environmental energy, which is varying with respect to the location. Hence it requires a high level complex simulation studies for estimation of the performance & energy potential of generation plant using the solar power applications [6, 7]. The Photo voltaic structure analysis design software is very significant in this engineering design process. There are many PV system installation design analysis software alternatives (e.g. the German Ministry for Economic Affairs and Energy *FreeGreenius* , the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM)) are available. NREL tools supports for design and modeling of advanced solar power plant as an option under open source license for estimation of the energy performance [8].This tools have models and algorithms for simulations and calculations. They supports for verification & validation task under research and publications work. these verification & validation research analysis helps the solar system designer and engineering teams in the different types of real-life projects for

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1Integral University, Lucknow - 226016, INDIA ORCID ID: 0009-0006-7148-3160
2 Integral University, Lucknow -226016, INDIA ORCID ID: 0000-0002-9409-9026
3Integral University, Lucknow - 226016, INDIA ORCID ID: 0000-0002-6039-094X
** Corresponding Author Email: asimamu@gmail.com*

templatization and automation of the design for solar power based generation plant and engineering process. This work is focusing on the NREL System Advisor Model (SAM) software for the Photo Voltaic system design and engineering process [9].

This organization of this paper is arranged as: the section 1, describing the requirement for choosing the resources renewable energy mainly solar power and the constraints that are associated with the analysis of its feasibility. Section 2, describing the brief overview and components selected for proposed roof mounted Photo Voltaic systems. Section 3 is describing the development of optimal design of 5 kW Photo Voltaic system under the consideration of the mono c-Si semiconductor material based solar modules using SAM tools of NREL. Section 4, describing the results & discussions that are generated for performance analysis of mono c-Si Photo Voltaic system. Finally the article is finished with summarized conclusions in the 5th section.

2. Methodology

If The NREL SAM's efforts behind development , research, demonstration and deployment is integrated with several weather data resources, the databases of component parameter associated to several organizations like the National Renewable Energy Laboratory (NREL), the Sandia National Laboratories, the University of Wisconsin (UW) and the California Energy Commission (CEC), the U.S. Department of Energy (DOE) etc [10]. The NREL based developed SAM software consist of several models to perform the calculation of the power output associated to several recent technologies like photovoltaic, concentrating photovoltaic, concentrating solar power and some financial models for calculating some financial metrics like net present value, payback period etc [11]. Many researchers have contribution of the study, work and models [12]. It has several updates & versions and this research study addressing the latest NREL SAM software release (Version 2021.12.2, 64 bit) [13].

The SAM is used for assisting solar stakeholders to assess the cost & performance of photovoltaic (PV) and concentrated solar energy based mode of generating the electricity. It also covers the additional renewable energy resources and been renamed the System Advisor Model from initial name of "Solar advisor model". It is incorporating the modules that are estimating the performance of different Photovoltaic and concentrated solar energy systems related design parameters and weather datasets files that are including irradiance, temperature, humidity etc. climate data for the desired location. The SAM is available at https://www.nrel.gov/analysis/sam/. The software is including the modules for power tower, parabolic trough, , linear Fresnel, and engine/dish systems. It incorporates the algorithms for estimating the levelized cost of electricity (LCOE) based on a selection of financial and incentive assumptions. The desired information for calculations of LCOE include the estimated operating & installed cost of desired technology.

There are multiple Photo Voltaic based technologies like monocrystalline silicon (Mono-Si or SC-Si), cadmium telluride (CdTe) etc having variation in cell efficiencies in the PV solar energy industry [14]. The analysis in this article investigates the Mono-Si PV cell technology. Mono-Si modules are mature photovoltaic technology that is widely deployed in commercial level planning with involvement of large grid connected PV solar power plant [15].

For running the simulations in SAM, various user supplied inputs are required. These are related to: (1) hourly data records of weather; (2) modules, inverters and array design & sizing specifications information; (3) effects of soiling; (4) effects of shading; and (5) AC/DC source related electrical losses. In the model developed in this article, it is assumed that the inverters, modules and tracking structure are in good working condition throughout the time defined under simulation.

2.1. Solar and weather data

The weather & solar datasets are stored as a CSV file containing information on the site's latitude, longitude, time zone & elevation.

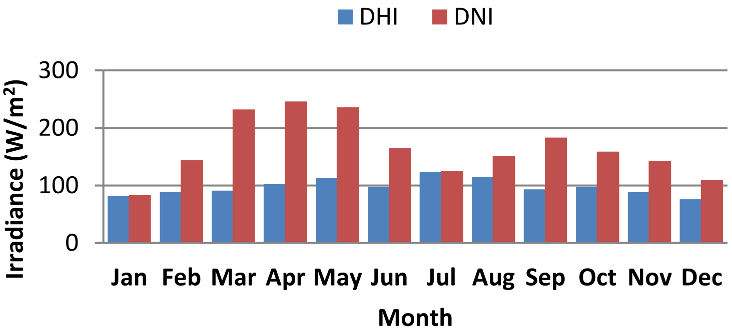

Fig 1. Monthly basis variation of DHI and DNI data of solar irradiance over a year.

The solar irradiance dataset recordings include the file related to the Direct Normal Irradiance (DNI), Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DHI). SAM software has an option for calculating DHI using internal evaluation of the sun position on considering the site's latitude, longitude, elevation of the and commencing time & date information for which the simulation is desired to run. This option are used during running of the simulations underpinning the reported results of this article (figure 1). The Perez model of Diffuse Sky is also used for determination of Plane-of-Array (POA) irradiance.

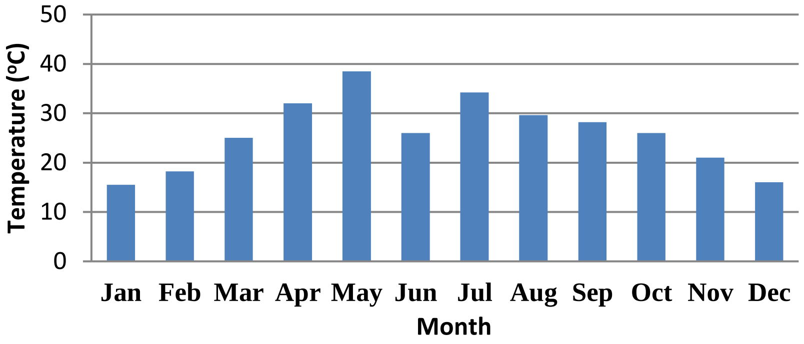

Fig 2. Monthly basis variation of temperature data over a year under simulation time

The DNI & GHI data are applied in the simulations and the actual DHI dataset included in the SAM CSV weather files were calculated using the equation given below:

$$DHI = GHI - DNI \times \cos(\text{sun\_zenith\_angle}) \quad (1)$$

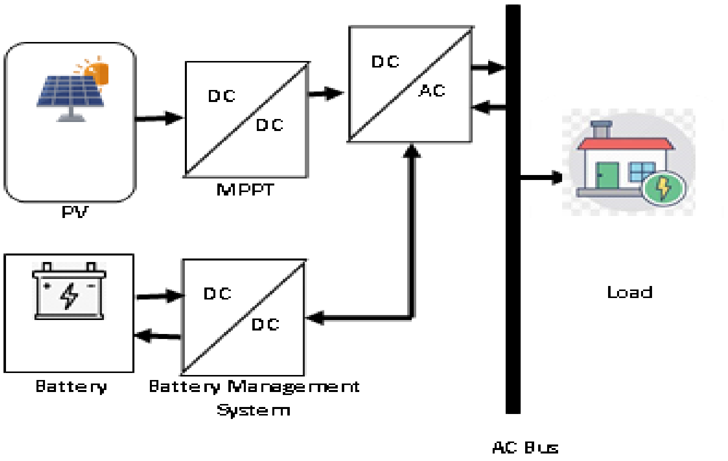

Fig 3. PV based DC connected behind the meter with battery storage system.

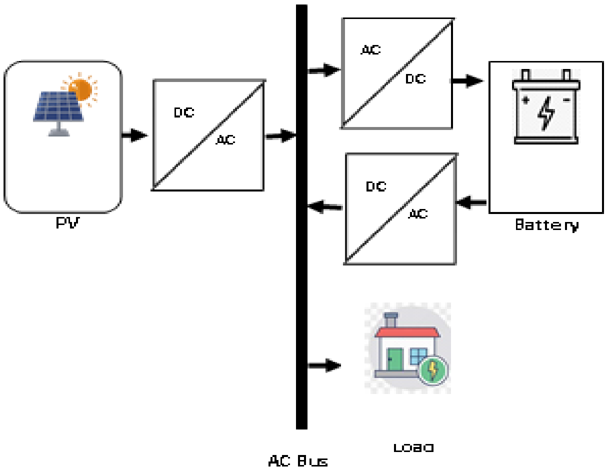

Fig 4. PV based AC connected behind the meter with battery storage system.

2.2. Module, inverter and solar array design

Required data for the technical specifications of the inverters & modules are described for running the simulation. As mentioned in the table 1, the module used is SunPower SPR-X21-335 (335W) while the inverters are SolarEdge technologies Ltd inverters (SE6000HUS(208V)). The technical parameters are set for devices using the product data sheets for the modules and inverters used during modeling in the SAM software. For establishing the module performance analysis, the model used in the SAM tool isbased on the 'California Energy Commission (CEC) Performance Model with parameters are specified by user. The required technical for the model entered in the SAM simulations are tabulated. This simulation use the coefficient calculator developed in Dobos (2012) for calculating the required parameters of the model using the standard specifications module from manufacturer's provided data sheets [17]. This simulation applies the NOCT cell temperature model for curve fitting of environmental temperature (fig 2).

The option applied for modeling the inverter is the implementation using the 'Inverter Datasheet' of the Solar Edge technologies technical parameters present in SAM simulations and listed in table 1. It is worthwhile to point that modules have 1 row and 10 columns array and a single inverter is used, with the AC output of inverter is specified at 5054W (5KW load) for the case described in this article.

SAM modeling implementation requires data related for system design features. In the sizing & design for the array, the desired information are: (1) modules number in a string; (2) strings number connected in parallel; & (3) number of inverters. Using these information and additional data specification related to inverters & modules following values of system performance are calculated: (1) maximum DC power generated from solar array; (2) maximum DC power given to the inverters as input and (3) maximum AC power obtained at the inverter output. The significant parameters for system design specified in the simulations using SAM are reported [18-20].

Table 1: System design parameters

(a)	**Location**	Lucknow
	Latitude	26.15
	Longitude	79.05
(b)	**Module database**	
	SunPower	SPR-X21-335
	Pmax	335W
	Vmax, Voc	57V,70V
	Imax, Isc	5.8A,6.2A
	Rows in array	1
	Column in array	10
	Material	Mono-c-Si
	Area	1.631m^{-2}
	Number of cells	96
(c)	**Inverter Database**	
	Solar Edge technologies	SE6000HUS(208V)
	Max AC/DC power	5054/5108 W
	Nominal AC/DC voltage	208/480V
	Max DC current	13 A
	Number of Inverter	1
	DC to AC ratio	0.93
(d)	**System Design**	
	DC capacity	4.693 KW
	AC capacity	5.054 KW
	Number of modules	14
	Number of strings	2
	Total module area	22.834 m^2
	Module per string in sub	7
	String V_{OC}	475V

	String V_{MP}	401V
	Maximum DC voltage	480V
(e)	**Battery Cell & System**	
	Lithium Ion	
	Desired Bank power	5KW
	Number of cell in series	3
	Number of strings in	1
	Battery Bank voltage	50.4 V
	Maximum charge	98.6 A
	DC to DC conversion	99%

Table 2: Electricity rates

Period	Tier	Max. Usage	Usage Units	Buy ($/kWh)
1	1	150	kWh	0.067
1	2	300	kWh	0.073
1	3	1e+38	kWh	0.08

The electricity rates are shown in the table 2.The above rates are charged as the tariff by the government organization to the residential customers. The rates are divided in three category (Tier) as the usage increased the tariff charges also increased as shown in the table 2.

3. Results

For the parameters and tariff rates (given in table 1 and 2) the analysis is performed for the performance results obtained using the SAM simulation tool

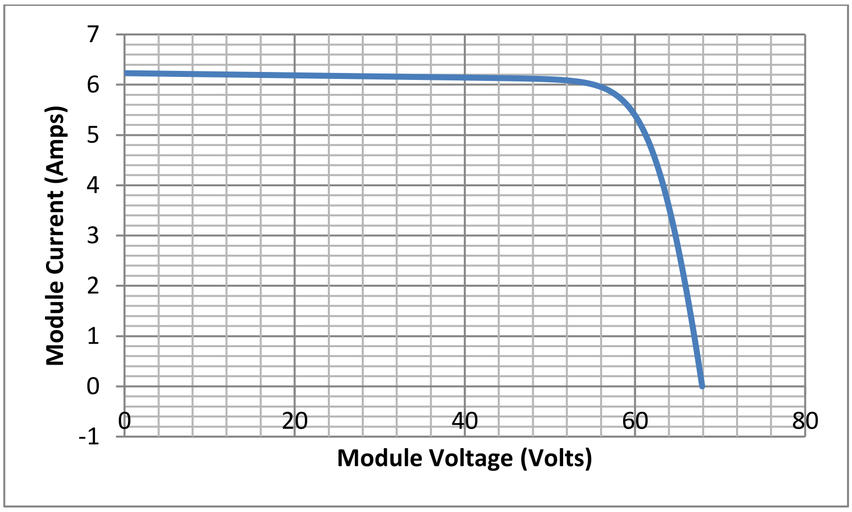

Fig 5. I-V curve for performance analysis of solar module (SunPower SPR-X21-335).

The solar module rated current ($I_{S.C.)}$) is observed to be 6.2 A and as the load decreases at the open circuit condition the current output is zero and the rate voltage output V_{OC} is observed to be 70V.Hence the I-V curve of figure 5 is satisfying the system parameters defined in table 1 for solar module (SunPower SPR-X21-335). In this paper since the AC or DC connected behind the meter system is discussed under techno-economical analysis. The system is using the power source as solar module. After the solar module inverter system module is connected. The percentage efficiency curve of inverter is shown in figure 6 at the generated percentage of rated output power. The percent efficiency varies in between 98 to 100% as the percentage of output is 10% to 50% of rate output power. Hence it shows that the selected inverter is perfectly matched to the DC put output of solar module and MPPT controlled output of DC -DC converters.

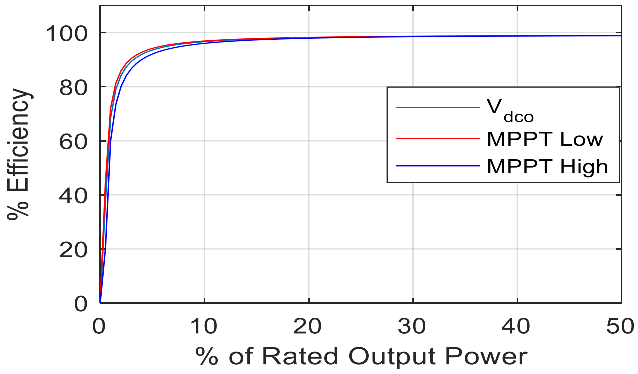

Fig 6. Percentage efficiency with respect to rated power for inverter (SE6000HUS).

The output of inverter module is directly used by residential or commercial load and given to the battery through the AC-DC converter with different connection arrangements as shown in figure 4 for DC or AC connected behind the meter system. The power when in excess is dispatched to the battery. Different dispatch methods to supply the power to battery with flexible schemes as per the solar irradiance condition and usage are proposed. In this paper four different dispatch mode for battery power are analyzed. These modes are:

1) Input grid power targets: Dispatch power to battery with respect to time based variation in grid power target data. It ensures that the power input from grid is below or at the levels of target power.

2) Peak shaving: Dispatch power to the battery in reference to achieve the target of reducing peak demand. It focus on electricity rate structure and targets to use the battery for reducing demand of billing.

3) Manual dispatch: It dispatches power to battery using month wise and hour wise provided schedules weekdays & weekend.

4) Price signal forecasting: Dispatch power to the battery for minimizing the energy and demand charge as per the electricity rates of billing.

The dispatch mode used under battery management system are applied here on Li-Ion battery. Presently different types of commonly used Li ion battery are available in solar powered isolated system. In this paper six different variants of Li-ion battery are considered under the performance analysis of behind the meter system. A short description of these six different battery types is given below:

(1) LMO/Graphite: Lithium Manganese Oxide (LiMn2O4 is an inexpensive high-voltage cathode material with high power capabilities but potentially lower lifespan.

(2) LFP/Graphite: Lithium Iron Phosphate (LiFePO4) is a lower voltage cathode material with excellent safety properties but lower volumetric energy.

(3) LCO/Graphite: Lithium Cobalt Oxide (LiCoO2) is a common cathode material with high specific energy, but potentially costly and toxic.

(4) LMO/LTO: Lithium Titanate (Li4Ti5O12) is promising anode material with excellent lifetime but low specific capacity & high cost.

5) NMC/Graphite: Nickel Manganese Cobalt (LiNiMnCoO2) is less expensive cathode material than LCO with potentially improved safety characteristics.

(6) NCA/Graphite: Nickel Cobalt Aluminum (LiNiCoAlO2) is similar in respects to NMC as a cathode material with high specific energy.

The results for DC connected behind meter system are shown in the table 3.

Table 3: Analysis of PV resource based DC connected behind the meter system
(*Yellow highlight :Best results & Pink Highlights: Worst result)

Dispatch Mode:	Battery Type	Annual AC energy (Year 1)	DC capacity factor Year 1	Energy yield in Year 1	Battery roundtrip efficiency	Levelized cost of energy real LCOE	Simple payback period	Net present value
		kWh	%	kWh/kW	%	Cent/kWh	Years	$
INPUT GRID	LMO/GRAPHITE	7529	18.3	1604	92.98	3.67	12.6	4126
	LFP/GRAPHITE	7557	18.4	1610	94.67	3	12.6	4838

	LCO/GRAPHITE	7554	18.4	1610	94.01	5.14	19.8	2592
	LMO/LTO	7545	18.4	1608	93.71	3.01	12.7	4820
	NMC/GRAPHITE	7519	18.3	1602	91.58	3.01	12.7	4810
	NCA/GRAPHITE	7562	18.4	1611	94.99	3.78	12.3	4024
PEAK SAVING	LMO/GRAPHITE	7565	18.4	1612	94.17	3.24	12.6	4597
	LFP/GRAPHITE	7563	18.4	1611	94.17	3	12.6	4848
	LCO/GRAPHITE	7562	18.4	1611	93.29	3.96	16.5	3839
	LMO/LTO	7555	18.4	1610	93.31	3.01	12.6	4832
	NMC/GRAPHITE	7538	18.3	1606	90.98	3	12.6	4832
	NCA/GRAPHITE	7566	18.4	1612	93.92	3.26	12.3	4572
MANUAL DISPATCH	LMO/GRAPHITE	7571	18.4	1613	**95.79**	3.33	12.6	4501
	LFP/GRAPHITE	7567	18.4	1612	95.31	3	12.6	4848
	LCO/GRAPHITE	7564	18.4	1612	94.61	4.47	16.2	3301
	LMO/LTO	7559	18.4	1611	94.39	3.01	12.6	4834
	NMC/GRAPHITE	7542	18.3	1607	92.01	3	12.6	4832
	NCA/GRAPHITE	7570	18.4	1613	95.66	3.36	12.3	4472
PRICE SIGNAL FORECAST	LMO/GRAPHITE	**7594**	**18.5**	**1618**	95.66	2.98	12.5	4880
	LFP/GRAPHITE	7593	**18.5**	**1618**	95	2.99	12.5	4874
	LCO/GRAPHITE	7593	**18.5**	**1618**	95.51	2.98	12.5	4885
	LMO/LTO	7554	18.4	1610	93.21	3.01	12.7	4830
	NMC/GRAPHITE	7590	18.5	1617	90.68	2.98	12.5	4879
	NCA/GRAPHITE	**7594**	**18.5**	**1618**	95.25	**2.92**	**12.2**	**4946**

(a) DC connected behind the meter system: In the table 3 first column depicts the name of different dispatch mode for battery power management system and the second column represents the six types of Li-ion batteries that are analyzed in this article. The result summary is given one by one under different performance metric parameters [21-25].

Annual AC energy (Year 1): The highest value of annual AC energy is observed for price signal forecast is 7594 kWh for LMO/Graphite and NCA/Graphite.

DC capacity factor (Year 1): The ratio of the predicted electrical output of system in the 1st year of operation to rated output. It is varying from 18.3% to 18.5%.Highest is observed for price signal forecast dispatch mode excluding LMO/LTO battery.

Energy yield in Year 1: It is the ratio of the annual AC electric output of system in Year 1st to the rated DC capacity. It is varying from 1602 kWh/kW to 1618 kWh/kW. Highest is observed for price signal forecast dispatch mode excluding LMO/LTO and NMC/Graphite battery.

Battery roundtrip efficiency: It is the ratio of total battery discharge energy w.r.t. battery charge energy in total life of the project. It is varying from 90.68% (NMC/Graphite under price signal forecast dispatch mode) to 95.79% (LMO/Graphite under manual dispatch mode).However under price signal forecast dispatch mode it is generally above than 95% for all batteries excluding LMO/LTO and NMC/Graphite.

Levelized cost of energy real LCOE: It is the total project lifecycle cost delivered by the system over its life load for behind-the-meter projects. The observed lowest cost is 2.92 cents/kWh (NCA/Graphite under price signal forecast dispatch mode) and highest is 5.34 cents/kWh (LCO/Graphite under input grid dispatch mode).

Simple payback period: It is time (years) takes for cumulative annual savings to equal the cumulative annual costs. Generally it is observed to be 12.2 to 12.7 years but the worst case is 19.8 years (LCO/Graphite under input grid dispatch mode) & best is 12.2 years (NCA/Graphite under price signal forecast dispatch mode).

Net present value: It is the measurement of economic feasibility of project that is including revenue and cost. Best value observed for (NCA/Graphite under price signal forecast dispatch mode) i.e. 4946 $ and worst is 2592 $ (LCO/Graphite under input grid dispatch mode).

(b) AC connected behind the meter system Similar to above results the techno economic analysis is also performed for AC connected PV resource based behind the meter system. The results are shown in table 4.In this table the observations of results in terms of different metrics are summarized below:

Annual AC energy (Year 1): Highest value under price signal forecast is 7592 kWh for [LMO,LFP and NCA] /Graphite and least is 7451 kWh for NMC/graphite under input grid dispatch mode.

DC capacity factor (Year 1): Varying from 18.1% to 18.5%.Highest for price signal forecast mode excluding LMO/LTO battery and lowest 18.1% (NMC/Graphite under input grid dispatch mode).

Energy yield in Year 1: Varying from 1588 kWh/kW to 1618 kWh/kW. Highest for price signal forecast excluding LMO/LTO and NMC/Graphite battery and lowest NMC/Graphite for input grid.

Battery roundtrip efficiency: Varying from 87.59% (NMC/Graphite under price signal forecast dispatch mode) to 91.85% (LMO/Graphite under manual dispatch mode).

Levelized cost of energy real LCOE: Lowest is 2.92 cents/kWh (NCA/Graphite under price signal forecast dispatch mode) and highest 5.18 cents/kWh (LCO/Graphite under input grid dispatch mode).

Simple payback period: The worst case is 20 years (LCO/Graphite under input grid dispatch mode) & best is 12.2 years (NCA/Graphite under price signal forecast dispatch mode).

Net present value: Best value observed for (NCA/Graphite under price signal forecast dispatch mode) i.e. 4945 $ and worst is 2537 $ (LCO/Graphite under input grid dispatch mode).

Table 4: Analysis of PV resource based AC connected behind the meter system

(*Yellow highlight :Best results & Pink Highlights: Worst result)

Dispatch Mode:	**Battery Type**	**Annual AC energy (Year 1)**	**DC capacity factor Year 1**	**Energy yield in Year 1**	**Battery roundtrip efficiency**	**Levelized cost of energy real LCOE**	**Simple payback period**	**Net present value**
		kWh	**%**	**kWh/kW**	**%**	**Cent/kWh**	**Years**	**$**
INPUT GRID	LMO/GRAPHITE	7494	18.2	1597	91.68	3.69	12.7	4093
	LFP/GRAPHITE	7489	18.2	1596	91.3	3.03	12.8	4772
	LCO/GRAPHITE	7487	18.2	1595	90.69	5.18	20	2537
	LMO/LTO	7478	18.2	1594	90.39	3.04	12.8	4753
	NMC/GRAPHITE	7451	18.1	1588	88.38	3.03	12.8	4745
	NCA/GRAPHITE	7494	18.2	1597	91.62	3.81	12.4	3968
PEAK SAVING	LMO/GRAPHITE	7515	18.3	1601	**91.85**	3.25	12.6	4562
	LFP/GRAPHITE	7513	18.3	1601	91.51	3.01	12.7	4805

	LCO/GRAPHITE	7515	18.3	1601	91.25	3.92	12.6	3872
	LMO/LTO	7509	18.3	1600	90.62	3.02	12.7	4789
	NMC/GRAPHITE	7492	18.2	1596	88.56	3.02	12.7	4791
	NCA/GRAPHITE	7519	18.3	1602	91.74	3.26	12.3	4562
MANUAL DISPATCH	LMO/GRAPHITE	7519	18.3	1602	91.63	3.35	12.7	4458
	LFP/GRAPHITE	7516	18.3	1601	91.17	3.02	12.7	4799
	LCO/GRAPHITE	7515	18.3	1601	90.54	4.5	16.3	3262
	LMO/LTO	7510	18.3	1600	90.3	3.03	12.7	4785
	NMC/GRAPHITE	7493	18.2	1597	88.14	3.02	12.7	4788
	NCA/GRAPHITE	7522	18.3	1603	91.58	3.38	12.3	4433
PRICE SIGNAL FORECAST	LMO/GRAPHITE	**7592**	**18.5**	**1618**	91.79	2.98	12.5	4879
	LFP/GRAPHITE	**7592**	**18.5**	**1618**	91.23	2.99	12.6	4873
	LCO/GRAPHITE	7591	**18.5**	**1618**	91.71	2.98	12.5	4885
	LMO/LTO	7533	18.3	1605	89.94	3.02	12.7	4796
	NMC/GRAPHITE	7589	**18.5**	1617	87.59	2.98	12.5	4878
	NCA/GRAPHITE	**7592**	**18.5**	**1618**	91.58	**2.92**	**12.2**	**4945**

4. Conclusion

In this article PV resource based behind the meter system is considered. The techno-Economic feasibility analysis is performed using SAM software tool. The analysis is performed for DC connected and AC connected behind the meter system. It is observed that the best battery power dispatch mode is price signal forecast mode. It is giving best value for al l the metrics. Using this mode the annual energy yield is highest hence it is giving least payback period of 12.2 years for both DC/AC connected behind the meter system.The best Li ion battery observed to be NCA/Graphite. It gives best values for all the metrics except the Battery roundtrip efficiency. The performance of DC connected system is slightly higher than AC connected system in case of annual AC energy and net present value.

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