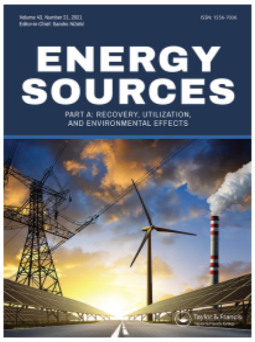

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Impacts of electricity pricing on techno-economic performance of photovoltaic-battery centered microgrid

Arvind Sharma and Mohan L. Kolhe

Department of Engineering and Sciences, University of Agder, Jon Lilletuns vei 9, NO 4879, Grimstad, Norway

ABSTRACT

The energy management technique in a microgrid, plays very crucial role for making it more economic viable during the electricity energy pricing dynamics. It is vital to investigate the impact of electricity energy pricing dynamics on operation and techno-economic performance of a micro-grid for maximizing the local energy participation with grid constraints. This paper has considered, a common PV-battery-based microgrid from Norway for assessing technical and economic performance with electricity energy pricing dynamics. In this work, energy management strategy has presented, for minimization of annual energy generation cost with maximization of battery energy throughput with grid constraints as network demand limits. It has been observed that grid buying price has more impacts on the cost of energy generation (CoE) as compare the grid selling price. While doubling the grid buying price, CoE is increased by 14% whereas doubling the grid selling price, CoE is reduced by 2%. This paper also included sensitivity analysis and analyzed that battery cost has highest impacts on CoE followed by PV cost and then grid tariffs. It has been noticed that doubling the cost of battery, PV and grid (one at a time) has increased CoE by 53, 31, and 27%, respectively. The operational energy management strategies presented in this paper, will certainly contribute for PV-battery-based micro-grid developments and evaluating operational performance under electricity energy pricing dynamics.

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Techno-economics; electricity pricing dynamics; energy management; battery; photovoltaic; microgrid

Introduction

The integration of PV system with battery has vast prospective to function as a microgrid and fulfill the local load demand during islanding mode and grid-connected mode. The operational performance of a PV-battery-based microgrid can be enhanced with suitable energy management strategies, and it can also contribute to demand-side management considering grid constraints. In the past few years, several research studies (Kumar et al. 2019; Khatib et al. 2015; Lang, Ammann, and Girod 2016; Liu et al. 2012) have been conducted, and these studies are mainly focused on technical sizing and performance evaluation of grid connected rooftop PV system, off-grid system, and hybrid energy systems for different geographical regions. The study presented in ref (Kumar et al. 2019), analyzed an ideal combination of a micro-hydro, photovoltaic, battery, and diesel generator to fulfill the electricity demand of rural village of Chamba District Himachal Pradesh in India however, this work has not included the sensitivity analysis of hybrid system with future energy tariffs. An optimization approach is used in ref (Khatib et al. 2015), for developing PV, wind and battery-based system for Kuala Terengganu, Malaysia whereas role of energy management strategy during grid outage conditions have not addressed. The cost-benefits analysis of grid-connected PV system in has been carried out in ref (Liu et al. 2012) considering the local climates, energy generation cost, emissions of the system, and

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CONTACT Arvind Sharma ✉ Arvind.Sharma@uia.no Department of Engineering and Sciences, University of Agder, Jon Lilletuns vei 9, NO 4879, Grimstad, Norway’

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return on investment. The study (Liu et al. 2012) has covered the impacts of PV system design the economics and environment however impacts of electricity energy tariffs on the techno-economic evaluation of the system has not covered. A techno-economic study of grid-connected PV system for residential and commercial consumers in Germany, Switzerland and Austria has presented in ref (Lang, Ammann, and Girod 2016). The paper (Lang, Ammann, and Girod 2016) analyzed the potential of considering rooftop PV for different consumers considering technological, economical, and geographical factors but dynamics of electricity pricing has not sufficiently covered. In the most of reviewed literatures (Kumar et al. 2019; Khatib et al. 2015; Lang, Ammann, and Girod 2016; Liu et al. 2012), impact of electrical energy pricing dynamics on techno-economic performance of microgrid system and role of energy management techniques for peak demand saving have not sufficiently covered.

Within Europe, interest of PV and battery system are also growing in the Nordic countries, due to economics & environmental concerns. In the Nordic countries, industry, commercial and households' consumers are seeking to reduce their electricity bills by integrating rooftop PV modules with batteries and it shows a vast prospective for peak load saving through PV-based micro-gird integration (Dale 2020). Within the Nordic countries, Norway is using mainly hydroelectricity (i.e., 96%), but in the recent years PV market has grown up as the installed cumulative PV capacity in Norway has reached 119.8 MWp at the end of 2019, and it was only 15.3 MWp at the end of 2015 (Dale 2020). It indicates that the PV market has increased eightfold in the last five years. It is mainly due to National policy such as Plusskundeordningen, subsidy payouts for small solar PV installations (National Policy 2020). The increasing PV penetration as well as energy market dynamics of the Norwegian system can contribute for local energy management for institutional systems to operate as microgrid. Some studies (Azmi 2017; Imenes et al. 2015; Sæle and Bremdal 2017; Sharma, Kolhe, and Sharma 2020), have reported operation of PV-based system in the Nordic climatic conditions. The performance evaluation of a grid-connected building integrated photovoltaic (BIPV) system in Norway has described with real functioning results in ref. (Azmi 2017). In the study (Azmi 2017), integration of an appropriate battery storage with grid constraints, has been highlighted for improving the operational performance of the grid connected BIPV system however, impact of electricity energy tariffs on the operational energy management strategies has not been discussed. In the ref. (Sharma, Kolhe, and Sharma 2020), the economic performance of BIPV system integrated with battery storage has been assessed under electricity energy pricing and grid constraints for a residential household, but it has not sufficiently included the energy management strategies during dynamics of energy pricing. The study (Sæle and Bremdal 2017), has focused on grid tariffs rates for domestic customers with rooftop PV system of Norway and presented how different grid tariffs can influence the cost-benefits. The results of study presented in ref (Sæle and Bremdal 2017), have shown that grid power tariff can provide more economic benefits to the prosumer compared to the grid energy tariff. The performance assessment results of a 45 kWp PV grid-connected PV system in Norway has reported in ref (Imenes et al. 2015). The paper (Imenes et al. 2015) highlights the growing interest in BIPV systems for residential homes as well as for larger industrial buildings, and also creates knowledge and valuable asset for planners in the building sector and grid operators. In the reviewed literatures (Azmi 2017; Imenes et al. 2015; Sæle and Bremdal 2017; Sharma, Kolhe, and Sharma 2020), technical and economic performance assessments of PV-battery-based microgrid under electricity energy pricing dynamics have not significantly analyzed for their role of energy management strategy in peak demand reduction with grid constraints.

In Norway, electricity energy tariffs have mainly two components; electricity price and grid rent. Based on the type of customers, electricity energy tariffs are divided into three types of contracts (Statistics Norway 2020): (i) Fixed price contracts: In this type of contract, grid tariff is fixed, or it associated with a fixed price route, are considered as fixed price contracts. (ii) Contracts tied to spot price: It includes contracts directly linked to the spot price in addition to the overhead charge or price ceiling. It has drawn from the elspot price (Statistics Norway 2020). (iii) Variable price contracts: In this category, price fluctuates during the year (e.g., quarterly), based on energy market demand. The electricity supplier is free to change any price but inform to the end user at least 14 days in advance.

These price contracts have applied to domestic, industries, and commercial buildings. It has observed that the average price of electricity from the year 2015 to 2018 had risen from 0.18 NOK per kWh to 0.41 NOK per kWh, and it is 135% greater relate to the 2015 (Hourly Electricity Price 2018). The annual variation of the electricity tariffs has shown in figure 1.

The average energy price of summer and winter seasons of 2015 have increased by 211and 88%, respectively, in the year 2018. Generally, average energy price of the summer period is lower compared to the winter period, but in the year 2018 the average energy of the summer season was 4.22% more compare to the winter season. The main reason for the increase in energy prices in the summer 2018 was the lack of rainfall in the year 2018 and therefore Norwegian hydropower generation was lower (Karagiannopoulos 2020). In addition to the load demand and electricity price's pattern in Norway, there are challenges with the distribution of the solar irradiance over the year, as very good amount of solar irradiance has been presented during the summer period, but very limited quantity has been presented in the winter season (Good, Lobaccaro, and Hårklau 2014). There are several industries, institutional and commercial buildings which have lot of potential to integrate PV & battery storage and have their specific demand patterns. Such consumers need to take immediate action on how they can reduce their load demand or use any other source of energy based on the electricity energy pricings. Therefore, technical, and economic performance analysis of PV-battery-based micro-grid system is essential for analyzing the effective usage of distributed energy sources and developing decentralized demand-side management techniques with grid constraints under dynamics of electrical energy pricing.

The main objective of this paper is to evaluate the technical and economic performance of PV-battery-based microgrid in Norway under dynamics of electricity energy pricing and increase the usage of distributed energy and effective battery participation for contemplating peak demand. This paper has been divided into six sections; the Section 1 has been providing introduction and details about the Norwegian electricity pricing. In the Section 2, operational energy management strategy has been discussed for techno-economic functioning of microgrid under market energy dynamic pricings. The operational analysis of the PV-battery-based microgrid system has been evaluated with different grid electricity energy tariffs (buying and selling) in the Sections 3 and 4, respectively. The impacts of different cost components on the economic parameters and battery energy performance (i.e. energy throughput), have presented in the Section 5. The functioning an PV-battery-based institutional energy system for operating it as a PV-based microgrid with the key economic advantages and future opportunities have been concluded in the Section 6.

System description of PV-battery-based microgrid

In this paper, a regular PV-battery-based micro-grid from Norway has considered for evaluating its techno-economic operational performance under dynamics of grid energy pricing. The considered PV-battery-based energy system consists of 800 kWp PV with 1 MWh li-ion battery and grid supply to

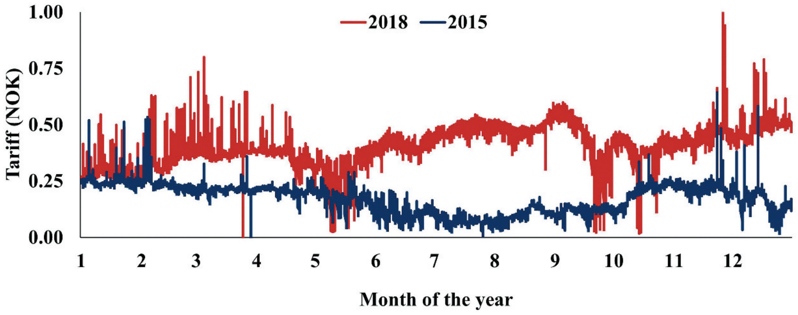

Figure 1. Electricity energy prices for years 2015 and 2018.

meet the local load demand. The block diagram of the considered PV-battery-based microgrid (Sharma et al. 2020), has illustrated in the figure 2.

In this paper, the institutional load profile has been considered from ref (Sharma et al. 2020) and its hourly variation has been shown in figure 3. The load profile of institutional building is used for evaluating the contributions from PV and battery for operating the system as a micro-grid. The peak demand has been observed 143.46 MWh and is considered as 1 p.u.

In this paper, the output of PV system (P_{PV}) has computed using solar radiation data accessible from the US National Renewable Energy Laboratory (Radiation Data of Solar 2020) (figure 4). Based on solar radiation data, the highest PV output was recorded at 0.73 p.u. in the September and February months. The output of PV for winter and summer periods are noted 35 and 65%, respectively, of the aggregated yearly PV output.

In this paper, depth-of-discharge, maximum state-of-charge, and efficiency of lithium-ion battery banks are 20, 100, and 90%, respectively (Sharma et al. 2020). For analyzing the battery performance, a parameter 'annual energy throughout' has used which represents the change in battery energy level in a month or year. It has been considered that 100% utilization of battery can produce 8.9 MWh (i.e., 0.062 p.u.) energy throughput in a month. As grid supply is relatively balanced in Norway thus grid failure scenario has not been considered. In this section, an energy management strategy has been proposed for improving the economic performance and operation of PV-battery-based microgrid system.

Micro-grid energy management strategy

In this study, the main objective of the energy management strategy has to lower peak requirement from the grid, and to increase PV contribution through optimal battery energy usage for meeting local demand considering market electrical energy pricing. A minimization approach (Kolhe, Iromi Udumbara Ranaweera, and Gunawardana 2013; Sharma et al. 2019) has applied for minimizing the overall energy generation cost (i.e., $f_{(cost)}$). The equation (1) is described as a function of energy generation cost (i.e., $f_{(cost)}$). The cost function has included energy cost from grid, reduction in peak demand cost and battery energy cost. In the equation (1), if $P_{Grid}(t)$-$P_{PV}(t)$ is positive (+ve) then price for grid purchase (i.e., $E_{Grid}(t)$) has considered and grid sell price (i.e., $E_{Sell}(t)$) will be zero whereas in case $P_{Grid}(t)$-$P_{PV}(t)$ is negative (-ve) then price for energy sell to grid ($E_{Sell}(t)$) is considered and price for grid purchase (i.e., $E_{Grid}(t)$) is zero.

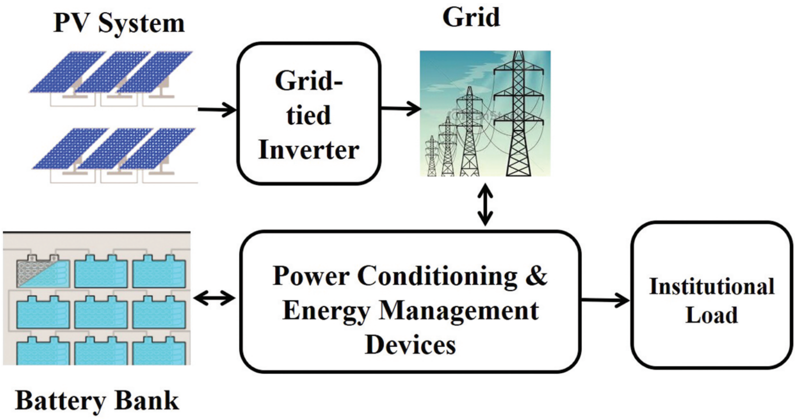

Figure 2. Illustration of PV-battery centered micro-grid system.

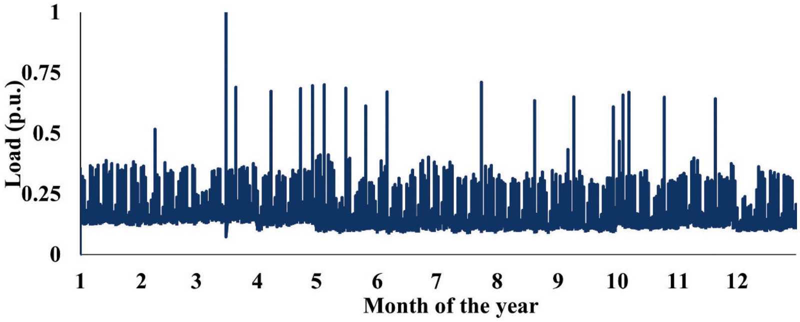

Figure 3. Load profile.

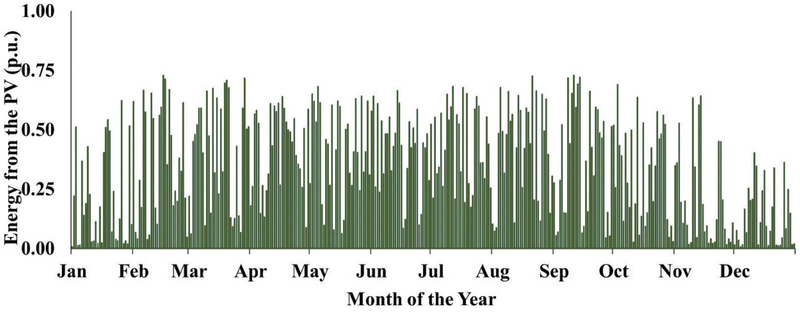

Figure 4. PV output profile.

$$\min f_{(cost)} = \sum_{t=1}^{T} \begin{bmatrix} [((P_{Grid}(t) - (P_{PV}(t)) * d(\Delta t)) * (E_{Grid}(t)] \\ +[((P_{PV}(t) - P_{Grid}(t)) * d(\Delta t)) * E_{Sell}(t)] \\ +[D_n(t) * (D_{Grid}(t)] \\ +[(P_{Bat}(t) * d(\Delta t)) * (E_{Bat})] \\ \end{bmatrix} \tag{1}$$

where:

T: Time interval in a year
$P_{Bat}(t)$: Power from the battery
P_{PV} (t): Power from PV
$D_n(t)$: Demand of grid electricity
$E_{Grid}(t)$: Grid electricity purchase price
$D_{Grid}(t)$: Demand price of electricity supply
$E_{Sell}(t)$: Selling price of grid electricity
$d(\Delta t)$: Time interval
E_{Bat}: Energy cost from battery
$P_{Grid}(t)$: Grid supply power'

The energy management technique presented in this paper has used for reducing the annual energy generation cost and grid's peak demand by increasing battery energy participation (i.e., energy throughput). The flow chart of the energy management technique has been illustrated in figure 5. In the beginning of the program at t = 0, the maximum grid power limits have been checked, and if the defined grid limits are greater than the load requirement then grid is managed the battery charging (in condition of $SoC(t) < SoC_{max}(t)$).

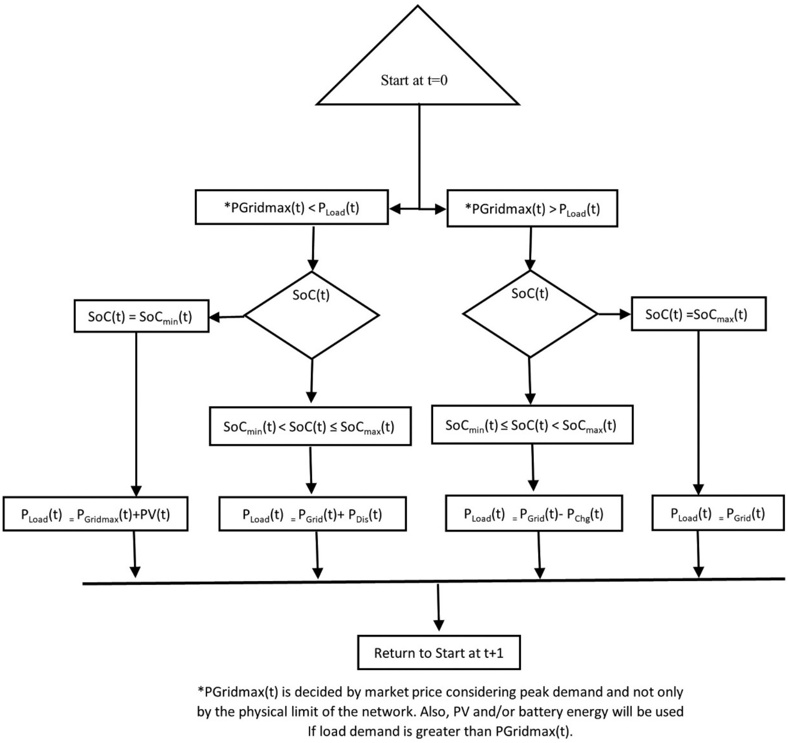

Figure 5. Flow chart of energy management strategy.

However, if the load demand exceeds the defined grid power limits then battery storage has used to fulfil the load demand (in condition of, $SoC_{min}(t) < SoC(t)$). After completing each (timesteps), program increased the time steps with $t = t + 1$ and verify the defined grid limits, and follow the same process as described above.

The considered PV-battery-based microgrid system is designed to meet the load demand even when grid has not available (i.e., in islanding mode). The schematic of the considered PV-battery-based energy system to function as microgrid has been shown in figure 2 (Sharma et al. 2020). The operational limits of the different components (i.e., PV, battery and grid) and their description, have explained in the subsequent sections.

Power generation and balance of distributed energy sources

In the equation (2), power generation from all local energy resources and their balance with time (t), have described.

$$P_{PV}(t) + P_{Dis}(t) + P_{Grid}(t) = P_{Load}(t) + P_{Chg}(t) + \ P_{Sell}(t) + P_{Loss}(t) \tag{2}$$

The considered PV-battery centered microgrid system is illustrated in figure 2 (Sharma et al. 2020) has taken as a unit, and the net energy provided to the grid has taken as $P_{PV}(t)$-$P_{Load}(t)$. In the equation (2), battery discharging and charging signs are considered as positive (+ve) and negative signs respectively. The institutional' s load with time t has represented by P_{Load} (t), and loss of power at time t has denoted by P_{Loss} (t).

PV array power output

In this work, PV array power output (P_{PV}) has calculated from ref (Radiation Data of Solar 2020). The minimum and maximum limits of PV array output have defined by $P_{PV}(t)$ in equation (3).

$$0 \leq P_{PV}(t) \leq \text{Max. } P_{PV}(t) \tag{3}$$

Energy contents in battery

In this work, it has been considered that initially battery has fully changed and its SoC has 100%; however, 80% of the battery capacity can be used for charging and discharging purpose. Equation (2) has been used for calculating energy content in the battery energy storage, and it has governed by battery energy throughput (Sharma et al. 2020). In the equation (4), limits of battery energy contents are given, and charging & discharging of the battery are described through equations (5) and (6), respectively.

$$SoC_{min} \leq SoC(t) \leq SoC_{max} \tag{4}$$

$$SoC(t) = SoC(t + \Delta t) - \frac{\eta_{Chg}.P_{Chg}(t).\Delta t}{C_{bat}} \tag{5}$$

$$SoC(t) = SoC(t + \Delta t) + \frac{P_{Dis}(t).\Delta t}{C_{bat} * \eta_{Dis}} \tag{6}$$

The parameters η_{Chg}& $\eta_{Dis}$are representing the charging and discharging efficiency of battery, and C_{bat} is battery capacity. The detail description of the selected key parameters for battery, e.g. 'depth of discharge', 'voltage of battery', 'capacity of battery', and 'lifetime throughput', have described in the Section 2 (Sharma et al. 2020). The economic methodology for calculating energy cost from the PV system have described in the Annexure I (Kolhe, Iromi Udumbara Ranaweera, and Gunawardana 2013; Sharma et al. 2019). The technical and operational performance of the PV-battery-based micro-grid system has assessed in the next section, considering different electricity energy tariffs (buying and selling) prices to grid.

Performance analysis of PV-battery-based microgrid with buying energy tariffs

In this section, impact of increasing grid electricity price (i.e. energy tariffs) on the operational and technical evaluation of the PV-battery-based micro-grids (i.e., figure 1) has been evaluated conspiring with energy management strategies. The electricity energy pricing has been taken from the NordPool market (Hourly Electricity Price 2018) and it has been noticed that the average price of electricity from the year 2015 to 2018 had risen from 0.18 NOK per kWh to 0.41 NOK per kWh, and it is 135% greater relate to the 2015. Therefore, variation of electricity energy prices has considered 100% (i.e., present price) to 200% (i.e., double), with variation of 25% intervals (i.e., 'Tariff @100%', 'Tariff @ 125%', 'Tariff @ 150%', 'Tariff @ 175%' and 'Tariff @ 200%') as shown in the figure 6. The Cases 'a', 'b', 'c', 'd', 'e' represent the tariff scenarios of 'Tariff @100%', 'Tariff @ 125%', 'Tariff @ 150%', 'Tariff @ 175%' and 'Tariff @ 200%,' respectively. The grid tariff has assumed to be fixed, for each case, during the project lifetime; and it is covered under the market inflation rate.

To evaluate the battery's performance, during the different energy tariffs, two cases have been analyzed by buying Tariff @100% (i.e., Case a) and Tariff @200% (i.e., Case e). In both scenarios, the energy management strategy is utilized for peak demand reduction as well as for market energy tariffs. Figures 7 and 8, have represented the energy contribution from PV, battery, and grid at Tariff @100% and Tariff @ 200%, respectively. In both Cases (i.e., Case a & Case e), it has been noticed that Grid and

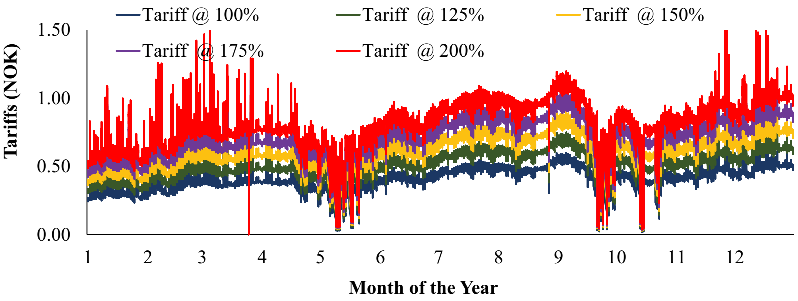

Figure 6. Different energy tariff.

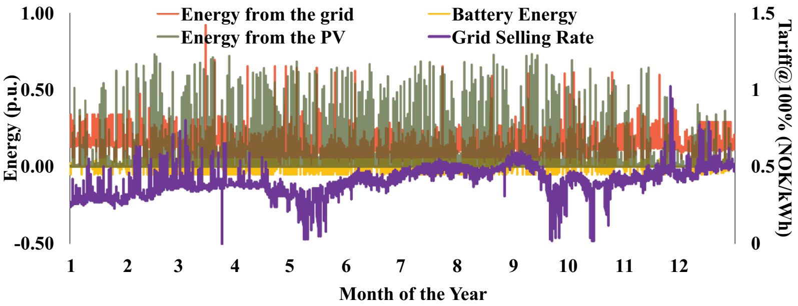

Figure 7. Grid, battery and PV energy @100% tariff (case a).

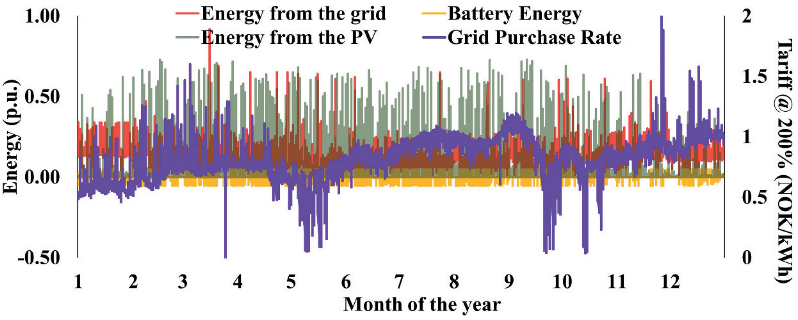

Figure 8. PV, grid and battery energy @200% tariff (case e).

PV energy contributions have not changed, however, the energy throughput of battery has increased in the Case e. During the day when grid energy tariff (i.e. buying) is high, the need of energy management technique for effective battery operation become very critical. To improve the economic profits from the PV-battery-based microgrid system, it has been considered that battery charging has taken place during non-peak hours so that the battery energy could be utilized in the best way.

It has been noticed that by increasing the grid energy tariffs, cost of electricity generation (CoE) and net present cost (NPC) of the PV-battery-based microgrid system have increased. The values of NPC and CoE have increased by 14% when electricity energy tariff has varied from 100 to 200%. In this analysis, the grid tariff is assumed to be fixed for each case during the project lifetime period, and it is included in the market inflation rate. It has been observed that increasing the grid tariffs has no impacts on the grid energy purchase and energy sold to the grid. If PV output is greater than the local load demand, then supplementary energy is used for battery charging through grid, and then remaining PV energy is considered to feed into the grid. It has noticed (table 1) that battery's participation (i.e., energy throughput) has increased by 3% with rise in grid tariff from 100 to 200%. The increase in the annual electricity bill has been recorded by 116% with tariff change from 100% to 200%. A variation in some of the selected economic parameters with increase in the electricity tariffs have presented in table 1.

The signs downward (↓) and upward (↑) indicate, percentage reduction and increment in the parameter's value.

The battery energy throughput and CoE with different energy tariffs have exhibited in figure 9. It has been observed that when grid buying tariff has increased by 100 to 200%, then battery energy throughput has increased by only 3%, whereas CoE has increased by 14%.

The monthly variation of electricity bills with different electricity energy tariffs (i.e. buying) have shown in figure 10. In this work, the eletricity bill has been calculated based on net energy buying from the grid. It has been noted that more electricity has been consumed during the winter season, and therefore the electricity bill in the winter period is 8% more as compare to the summer period. The PV generation is lower during winter season and therefore more grid energy has used for meeting the load demand. In the summer season, PV has generated 65% of the total annual energy generation, and during this period if PV power output has more than load demand, then the additional energy has considered feeding into the grid.

A monthly variation of energy sold with different tariffs, to the grid has illustrated in figure 11. It has been noticed that more energy has been sold to the grid during summer season. The energy sold to the grid in the summer season has represented 73% of the annual energy sold to the grid. However, with the increase in grid tariffs has not reflected any impacts on the electricity sold to the grid. It has noticed that no change in the graph of shape of the electricity sold to the grid, when tariff (buying) has increased from 100% to 200% and its variation has illustrated in figure 11.

It has noticed that energy management strategy performs very crucial role to optimize battery operation during the different grid tariff scenarios. It has been observed that economic and technical evalution of the PV-battery-based microgrid system has improved with effective and efficient application of battery storage. The grid demand charges and energy tariffs may increase in the near future for industrial and commercial power consumers. Therefore, presented results on the PV-based microgrid are going to be beneficial for evaluating technical and economic operational performance under different electricity energy tariff scenarios. In the next section, operational performance of the PV-battery-based microgrid has analyzed with different electricity selling price to the grid.

Table 1. Economic analysis of micro-grid with different grid tariffs.

Performance parameters	Different Grid Tariff Rates @100% (Case a)	Changes in % as compare to the tariff @100% (Case a) @125% (Case b)	@150% (Case c)	@175% (Case d)	@200% (Case e)
Net present cost (10^6 NOK)	56.6	4 (↑)	7 (↑)	11 (↑)	14 (↑)
CoE (NOK)	1.80	4 (↑)	7 (↑)	11 (↑)	14 (↑)
Total grid energy purchased (MWh)	1188	0	0	0	0
Total energy sold to the grid (MWh)	162	0	0	0	0
Total battery energy throughput (MWh)	54	0	1 (↑)	2 (↑)	3 (↑)
Annual bill (10^3 NOK)	420	29 (↑)	58 (↑)	87 (↑)	116 (↑)

The signs downward (↓) and upward (↑) indicate percentage reduction and increase in the parameter's values, respectively.

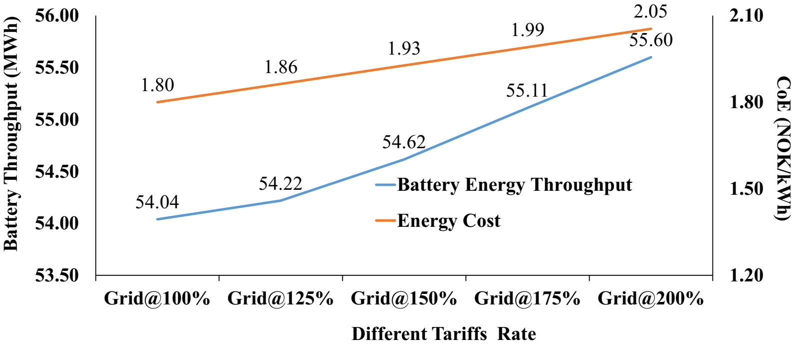

Figure 9. CoE and energy throughput of battery with tariffs (i.e. buying).

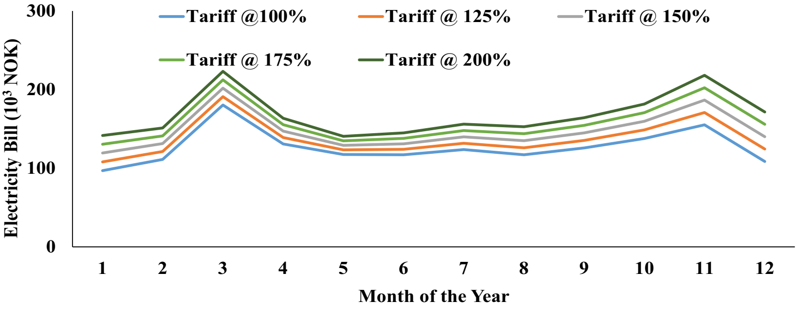

Figure 10. Electricity bill with different energy tariffs (i.e. buying).

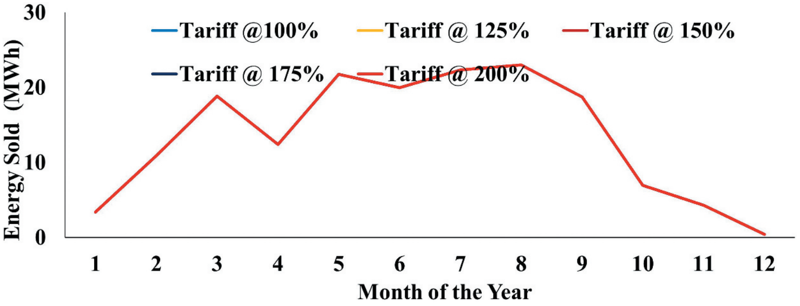

Figure 11. Energy sold to the grid with diferent energy tariffs (i.e. buying).

Performance evaluation with grid selling prices

In this part, technical and economic functioning of the PV-battery-based micro-grid has evaluated with increasing grid energy selling prices. The considered electricity selling prices have increased with a rate of 25% of the real time tariff of the year 2018. The Cases f, g, h, i and j represent the electricity selling price scenarios of ‘Selling @100%’, ‘Selling @ 125%’, ‘Selling @ 150%’, ‘Selling @ 175%’ and ‘Selling @ 200%,’ respectively, and its illustration have displayed in figure 6. The role of energy management strategy and battery energy storage becomes very crucial during the period of higher selling price. To enhance the technical performance and economic benefits from the PV-battery-based microgrid system, it has been assumed that battery charging has taken place during non-peak hours. Therefore, it is vital to use the battery energy in the appropriate way, especially during the peak hour demand when grid electricity (i.e., buying) prices are higher.

In this work, a comparison of two cases have considered for analyzing the performance of PV-battery-based microgrid with Selling @100% (i.e., Case f) and Selling @200% (i.e., Case j) with fixed grid buying Tariff @100%. In both scenarios, energy management strategy has utilized for peak demand load reduction under electricity energy tariffs. The energy contribution from PV, battery, and grid for Selling @ 100% and Selling @ 200%, have exhibited in figures 12 and 13, respectively. It has been noticed that in both Cases f & j, PV, grid and battery energy contributions have not changed.

It has been observed that with increase in the electricity energy tariffs, NPC and CoE of the PV-based microgrid system have decreased. The value of NPC and CoE has decreased by 2%, when grid selling price has varied from 100 to 200% with fix buying energy tariff of 100%. It has been noticed that energy bought from the grid has increased by only 1% when grid electricity selling price is increased to 200% from 100%. It has been observed (table 2) that there are no significant changes in the battery participation (i.e., energy throughput) when selling price is rose from 100 to 200%. The reduction in the annual electricity bill has seen 17% with grid selling price changes from 100 to 200%. A variation of selected economic parameters with rise in the grid selling price have given in table 2.

The signs downward (↓) and upward (↑) indicate, percentage reduction and increment in the parameter's value.

The battery energy throughput and CoE' changes with different energy tariffs have been shown in figure 14. It has been observed that when grid selling price has increased by 100% to 125%, the CoE has not changed, whereas CoE has decreased by only 2%, when grid selling has changed to 200%.

The monthly variation of electricity bill with different grid selling price have shown in figure 15. In this work, the electricity bill has been calculated based on net energy bought from the grid. It has noted that the grid selling price has more impacts on the electricity bill during winter season. The lower PV generation during winter period, has compensated by the grid for meeting the load demand. In the summer season, PV has generated 65% of the total annual energy generation and during this period excess PV generation has fed into the grid as grid selling price is higher.

A monthly variation of energy sold to the grid with different grid selling price have shown in figure 16. In the summer season more energy has sold to the grid and it has 72% of the total annual energy sold to the grid. It has been observed that the energy sold to the grid has increased by only 4% when grid selling price has increased from 100% to 200%. More PV energy has fed into the grid as grid selling prices have increased, making PV-battery-based microgrid systems more economical.

Impact of PV, battery's cost, and energy tariff on the CoE

The cost of different components e.g., PV, battery, power conditioning devices and energy tariffs, have significantly influenced the techno-economic evaluation of the PV-battery centered microgrid. However, the cost of PV, battery and grid tariff represent significant share of the NPC and therefore the impacts of PV, battery's cost, and grid energy tariffs on CoE have analyzed. The multiplier factors of 0.5, 1, 1.5, and 2 have considered for PV and battery system, whereas multiplier factors of 1, 1.25, 1.5, and 2 have taken for grid tariff. The multiplier factor '1′ represents the base case scenario having component cost as described in Case a. The multiplier factors '0.5′, '1′, 1.5′ and '2′ represent the change in components costs based on the Case a. In figure 17, 'BBx0.5′, 'BBx1′, 'BBx1.5′ and 'BBx2′ are representing battery cost with multiplier factors of '0.5′, '1′, '1.5′ and '2′, respectively. In this study, available battery energy has been utilized for peak load saving. Also, the grid buying & selling prices have fixed at 100% (i.e. Case a).

It has been noticed (figure 17) that multiplier factors of 0.5, for PV (PV x 0.5) & battery (BB x 0.5) and unit factor for energy tariff (Tariff x 1) have reduced the CoE by 42% whereas with multiplier factor '2′ for energy tariff (Tariff x 2) has reduced the CoE by 23%. To evaluate the

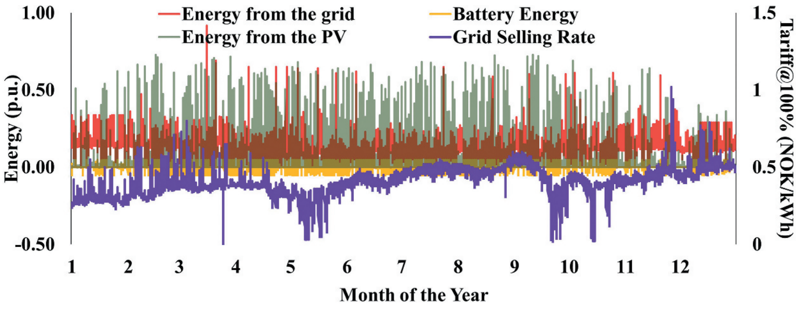

Figure 12. PV, grid & battery energy for grid selling price @100% (case f).

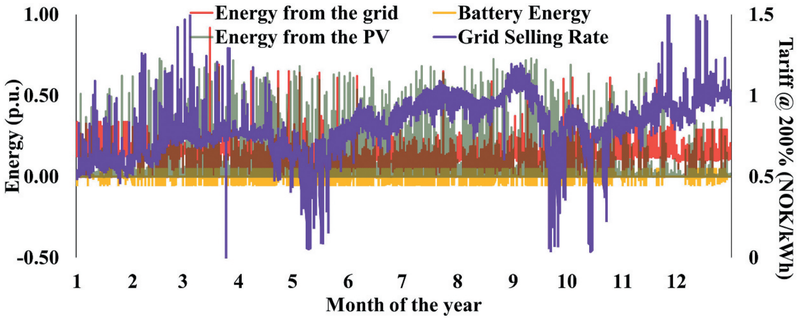

Figure 13. PV, grid & battery energy for grid selling price @200% (case j).

impact of grid tariff on the CoE, multiplier factor has been kept at ‘1′ for PV (PV x 1), and battery (BB x 1), whereas the multiplier factor of energy tariff has changed from 1 (Tariff x 1) to 2 (Tariff x 2). It has been observed that by changing the tariff multiplier factor from 1(Tariff x 1) to 2 (Tariff x 2), CoE has increased by 27%. Similarly, for analyzing the impact of battery cost on the CoE, multiplier factor has kept ‘1′ for PV (PV x 1) and energy tariff (Tariff x 1) whereas the multiplier factor of battery cost has changed from 1 (BB x 1) to 2 (BB x 2) and 0.5 (BB x 0.5). It has been observed that by changing the multiplier factor of battery cost from 1 (BB x 1) to 2 (BB x 2) and 0.5 (BB x 0.5), CoE has increased by 53% and decreased by 27%, respectively. In the same way, the impact of PV cost on the CoE has been analyzed and therefore multiplier factor has kept ‘1′ for battery (BB x 1) for battery and energy tariff (Tariff x 1) whereas the multiplier factor of PV

Table 2. Econmic analysis with grid selling prices.

Performance parameters	Different selling prices to grid				
	Changes in % as compare to grid selling price @100%				
	@100% (Case f)	@125% (Case g)	@150% (Case h)	@175% (Case i)	@200% (Case j)
Net present cost (10^6 NOK)	4.28	0	1 (↓)	2 (↓)	2 (↓)
CoE (NOK)	1.35	0	1 (↓)	2 (↓)	2 (↓)
Total grid energy purchased (MWh)	1197	0	0	0	1(↑)
Total energy sold to the grid (MWh)	174	0	0	0	4 (↑)
Total battery energy throughput (MWh)	42414	0	0	0	1 (↓)
Annual bill (10^3 NOK)	420	4 (↓)	8 (↓)	12 (↓)	17 (↓)

The signs downward (↓) and upward (↑) indicate percentage reduction and increase in the parameter’s values, respectively.

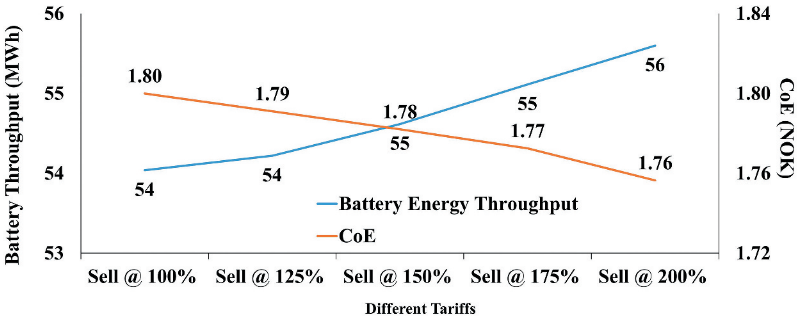

Figure 14. CoE and energy throughput of battery with grid selling prices.

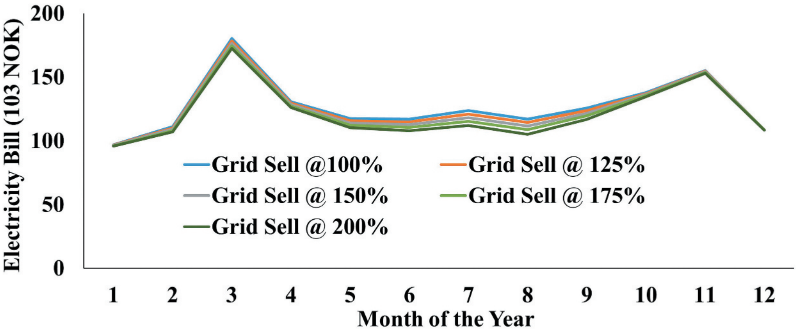

Figure 15. Electricity bill with different grid selling prices.

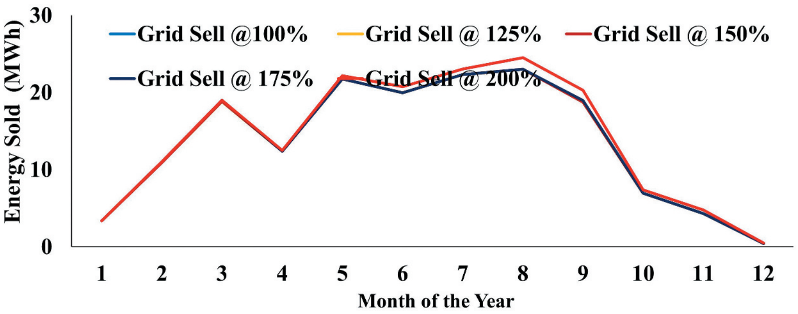

Figure 16. Energy sold to the grid with different grid selling prices.

cost has changed from 1 (PV x 1) to 2 (PV x 2), and 0.5 (PV x 0.5). It has been observed that changing multiplier factor of PV cost from 1 (PV x 1) to 2 (PV x 2) and 0.5 (PV x 0.5), the CoE has increased by 31% and decreased by 15%, respectively. The performance evaluation of all cases has been verified with the 'Homer Pro' tool (HOMER Pro Ver. 3.13 2020). After analyzing the impacts of various components 'cost on the energy generation cost of microgrid, it has been concluded that battery cost has higher impact on the CoE as compared to PV and energy tariff. It has been found that throughout the project lifetime of 25 years, percentage cost contribution of PV, battery, grid, and micro controller in the microgrid system have 39, 27, 21, and 13%, respectively, in Case a.

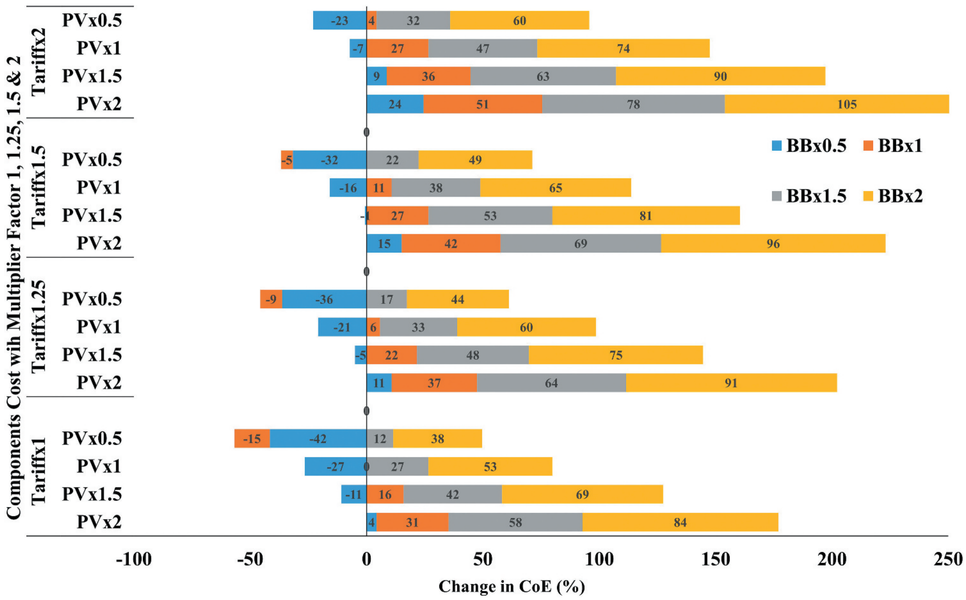

Figure 17. Variation of CoE with PV, battery and grid traiffs.

Conclusions

In this work, technical and economic performance evaluation of the PV-battery centered microgrid has evaluated with an energy management technique. The presented energy management strategy has used for enhancing the contribution of the local distributed sources with reduction in grid demand during peak hours under electrical energy pricing dynamics. The value of NPC and CoE have increased by 14%, when electricity energy (i.e., buying) tariff has varied from 100% to 200%. The energy throughput of battery has not changed when tariff (i.e., buying) has varied from 100 to 125% however it has increased by only 3% with rise in tariff (i.e., buying) from 125 to 200%. The increase in the annual electricity bill has been recorded by 116% with change in the buying tariff from 100 to 200%.

The value of NPC and CoE have decreased only by 2%, when the grid selling price has changed from 100 to 200%. The reduction in the annual electricity bill has been observed by 17% with change in the energy selling price from 100% to 200%, at fixed grid buying tariff at base case. It has been found that throughout the project lift time of 25 years, the cost contribution of PV, battery, grid and micro controller in the microgrid system have share of 39, 27, 21, and 13%, respectively, in the base case (i.e., Case 1).

Outcomes from this paper will be beneficial for utility companies, electricity regulatory authorities, policy makes for analyzing the operation and future planning of the PV-battery-based microgrids with electricity energy pricing dynamics.

Notes on contributors

Dr. Arvind Sharma has PhD (2021) from University of Agder (Norway). He is working with The Energy and Resources Institute (TERI), India in the Renewable Energy Technologies Division as Fellow from 2007 to till date. At TERI, he has actively contributed to the flagship program ‘Lighting a Billion Lives©’ for developing solar charging station for off-grid rural electrification.

Professor (Dr) Mohan Kolhe is with the Faculty of Engineering and Science as full professor in Energy Systems Engineering with focus on Smart Grid and Renewable Energy Systems. He has more than three decades of academic experience at international level on electrical and renewable energy systems. He has previously held academic positions at the world's prestigious universities e.g. University College London (UK / Australia), University of Dundee (UK); University of Jyvaskyla (Finland); and Hydrogen Research Institute, QC (Canada). He was a member of the Government of South Australia's first renewable energy board (2009-2011). His academic work ranges from the smart grid, grid integration of renewable energy systems, energy storage, electrical vehicles, home energy management system, integrated renewable energy systems for hydrogen production, techno-economics of energy systems, solar and wind energy engineering, development of business models for distributed generation.

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Annexure –1

Energy generation cost of PV System

The levelized energy cost calculation and replacements of the system components based on technical operational functions have been described in the previous work [Kolhe, M. et al. 2002]. The PV system generation cost ($\mathrm{CoE}_{\mathrm{sys}}$) has been calculated by (7). The cost of inverter and battery are considered as part of PV system.

$$CoE_{sys} = \frac{NCF_{SYS} * CRF_{pv}}{\sum_{m=1}^{12} n_D * M_{pv}} \tag{7}$$

where, $\mathrm{n_D}$ is the number of days in a month, $\mathrm{M_{pv}}$ monthly average per day generated by PV system. The capital recovery factor ($\mathrm{CRF_{pv}}$) is given by (8).

$$CRF_{pv} = \left(\frac{b}{1-(1+b)^{-M}}\right) \tag{8}$$

where, b is the discounted rate, M is project lifetime, NCF $_{\mathrm{SYS}}$ is the total net present cost of PV system and it is the sum of investment cost of PV (C $_{\mathrm{PV}}$), battery cost (CBatt), operation and maintenance cost ($\mathrm{OM_{SYS}}$) and replacement ($\mathrm{R_{RYS}}$) of PV system. $\mathrm{NCF_{SYS}}$ is defined by the (9).

$$\mathrm{NCF}_{SYS} = \mathrm{C}_{PV} + \mathrm{C}_{Batt} + \mathrm{OM}_{SYS} + R_{RSYS} \tag{9}$$

PV system maintenance and operation costs

Maintenance and operation cost ($\mathrm{OM_{SYS}}$) includes maintenance, recuring costs, tax, indemnity, etc. It is given as a percentage (i.e. k) of initial investment ($\mathrm{C_{SYS}}$) of PV system. For a first year, the maintenance and operational cost is ($\mathrm{OM_0 = k(C_{SYS})}$). It is increased at a rate a0 and discounted at rate b. The $\mathrm{OM_{SYS}}$ during life time of M years is given by (11):

$$\mathrm{OM}_{SYS} = \mathrm{OM}_0\left(\frac{1+a_0}{b-a_0}\right) * \left[1-\left(\frac{1+a_0}{b-a_0}\right)^{M}\right] \mathit{if}\ b \neq a_0 \tag{11}$$

$$\mathrm{OM}_{SYS} = \mathrm{OM}_0 * M\ \mathit{if}\ b = a_0 \tag{12}$$

PV System *Replacement cost*

The replacement cost ($\mathrm{R_{SYS}}$) is calculated using cost of inverter and battery replaced within the system lifetime of M years (). The replacement cost of inverter ($\mathrm{R_{INT}}$) and battery system ($\mathrm{R_{Bat}}$) is mainly a function of replaced number of inverters (u) battery (v) over the system lifetime, without taking the salvage value of replaced inverter and batteries into consideration. It is given described by (13) and (14) respectively.

$$R_{INT} = \sum_{j=1}^{w} C_{INV} * \left(\frac{1+a_0}{1+b}\right)^{\frac{Mj}{u+1}} \tag{13}$$

$$R_{Bat} = C_{Bat}\sum_{j=1}^{x}\left(\frac{1+a_0}{1+b}\right)^{\frac{Mj}{v+1}} \tag{14}$$

$$\mathrm{R_{SYS}} = \mathrm{R_{INT}} + \mathrm{R_{Bat}} \tag{15}$$