CSTEP
CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

Solar Energy-Based EV charging:

A Pilot and Techno-Economic Study

Submitted to

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BESCOM

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SHAKTI
SUSTAINABLE ENERGY FOUNDATION

Solar Energy–Based EV Charging: A Pilot and Techno-Economic Study

Center for Study of Science, Technology and Policy

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Disclaimer

Shakti Sustainable Energy Foundation seeks to facilitate India's transition to a sustainable energy future by aiding the design and implementation of policies in the areas of clean power, energy efficiency, sustainable urban transport, climate change mitigation, and clean energy finance.

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Executive Summary

India has 21 of the 30 cities with the worst air quality in the world. The transport sector is a major contributor (40%–80%) to air pollution in the cities. Hence, decarbonising the transport sector with the deployment of electric vehicles (EVs) is a crucial step in mitigating air pollution. Running an electric vehicle in the USA leads to a greater reduction in CO_2 emissions than running it in India since the grid energy (used by the EV) in India is predominantly generated using coal. Therefore, the renewable energy mix of grid electricity becomes essential in enabling green mobility in the truest sense. The Center for Study of Science, Technology and Policy's (CSTEP's) pilot project at the Bangalore Electricity Supply Company (BESCOM) Corporate Office premises aims to demonstrate this concept of using a clean source of energy (solar) for charging EVs.

The system design for the pilot project consists of a power conversion unit (PCU), solar rooftop photovoltaic (SRTPV) panels, a lithium-ion battery bank, and an EV charger as the main components. An intelligent computing unit in the PCU commands the energy flow across these components to maximise the generated solar energy for self-consumption.

The project showcases

- an intelligent bi-directional converter (PCU) that interfaces with SRTPV and battery systems (with DC coupling) to manage the energy flow with EV chargers and the grid.
- the prioritisation of solar energy for local consumption before feeding it to the grid.
- the deployment of a novel charging algorithm where the EV charging load is made to follow the solar energy generation profile. Such a method reduces the need for a costly battery energy storage system (BESS).

A novel framework to estimate the levelised cost of charging (LCOC) at a certain electric vehicle charging station (EVCS) with grid-connected RTPV and RTPV plus energy storage is also provided in the report. The framework can be extended to assess the feasibility of using a grid-tied RTPV plus energy storage system serving any electrical load in general. Key learnings from our analysis are as follows:

- EVCSs with SRTPV are economically more viable than EVCS with grid. The mismatch between solar energy generation and consumption (from charging) can be solved by deploying net-metering at charging stations.
- A battery storage capacity equal to 40 kWh was considered in the analysis, which stored approximately 16% of the total daily solar energy (on average) generated. The costs of upstream electricity for grid only, PV only, and PV plus BESS are INR 5, INR 4.6, and INR 8.9, respectively. Including a BESS increased the cost of PV+storage system electricity by INR 5.3/kWh.
- Among the scenarios considered, an EVCS connected to RTPV under net-metering policy represents the best-case scenario with the least LCOC (Chapter 5).

Currently, only EVC guidelines are in place, sourcing the power either from renewable energy sources is not emphasised. Learnings from the study can, therefore, guide policies for the widespread adoption of SRTPV-based EVCSs.

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Abbreviations

EV	Electric vehicle
SRTPV	Solar rooftop photo voltaic
kWp	Kilowatt peak
MW, GW	Megawatt, gigawatt
Ah	Ampere hour
DHI	Department of Heavy Industries
FAME	Faster Adoption and Manufacture of (Hybrid and) Electric Vehicles
OEM	Original equipment manufacturer
EVCS	Electric vehicle charging station
EVSE	Electric vehicle supply equipment
CMS	Central monitoring system
BESCOM	Bangalore Electricity Supply Company
MPPT	Maximum power point tracking
PCS, PCU	Power conversion system, power conversion unit
IGBT	Insulated-gate bipolar transistor
EMS	Energy management system
BMS	Battery management system
BESS	Battery energy storage system
SoC	State of charge
DEIPL	Delta Electronics India Private Ltd.
O&M	Operations and maintenance
LCOC	Levelised cost of charging
LCOE	Levelised cost of energy
LCOS	Levelised cost of storage

1. Introduction

Many countries are aggressively pursuing electric vehicles (EVs) as one of the many ways of addressing climate change. The objective is to replace the more polluting internal combustion engine (ICE) with electric motor and battery–enabled vehicles that can reduce the carbon footprint associated with transportation. Technological innovations over the years, especially in battery technology, are driving the transition to EVs, though their adoption is still at a nascent stage. Major challenges include relatively high upfront costs, range anxiety, inadequate charging infrastructure, and considerable waiting time for recharging batteries. While upfront costs are expected to reduce in the coming years due to technological improvements and economies of scale, the planning of adequate charging infrastructure will require an initial push by the Government of India and the authorities concerned. It should be noted that the energy mix of the grid electricity driving the EVs also plays an important role in achieving green mobility.

Owing to their zero tailpipe emissions, EVs are expected to counter the harmful effects of emissions from fossil fuel–based vehicles. However, it is important to note that EVs are sustainable in the long run only if they run on a cleaner form of energy. Currently, the primary source of energy in the electrical grid is predominantly coal. EVs sourcing energy from renewables, therefore, represent green mobility in the true sense of the phrase. Solar rooftop photovoltaic (SRTPV) is a popular technology to source clean energy and can be easily scaled within cities. SRTPV systems offer a number of advantages in EV charging:

- They are easy to install because of their modular design.
- They are a cost-effective alternative to charging from the grid.
- They can help reduce the detrimental effects of a surge in EV charging demand on the grid.

In this regard, the report explores the possibility of using solar energy for achieving a greener and more sustainable mode of transportation. The study showcases a pilot demonstration of an on-grid solar EV architecture, which could be further examined for large-scale implementation.

1.1. Electric Vehicle Scenario in India and Karnataka

The transport sector in India is largely dominated by two- and three-wheelers, jointly accounting for 83% of the total number of vehicles in the country. Two-wheelers are expected to lead the EV transition, given the advantages of affordability and ability to conduct short-distance trips with reduced range anxiety. Currently, both two- and three-wheelers lead the EV sales. The number of electric two-wheeler units sold in 2016–17 was 23,000, which increased by 138% to 54,800 units in 2017–18. This increase was despite a reduction in the sale of electric four-wheelers (see Table 1).

Table 1: Total EV sales in India

EV Segment	FY 2016–17	FY 2017–18	FY 2018–19	FY 2019–20
Two-wheelers	23,000	54,800	1,26,000	1,52,000
Three-wheelers	n/a	5,20,000	6,30,000	90,000
Four-wheelers	2,000	1,200	3,600	3,400
Buses	n/a	n/a	400	600
Total	**25,000**	**5,76,000**	**7,59,000**	**2,46,000**

Source: Electric Vehicle Sales Data – India (2018); Jain (2020); Wadhwa (2019)

Karnataka aims to establish itself as a major destination for EV manufacturing. In this regard, the state government wants to make Bengaluru the "Electric Vehicle Capital of India". As shown in Table 2, the current number of EVs in each segment in the city is considerably lower and forms a very small percentage of the total vehicle population in the city, which is around 77 lakh.

Table 2: Current EV population in Bengaluru city

Vehicle Type	Total Vehicle Population	EV (as of January 2021)
Two-wheelers	57,72,673	11,192
Three-wheelers	2,01,017	258
Four-wheelers	17,13,023	5,778
Buses	50,988	Nil
Total	**77,37,701**	**17,228**

Source: B.PAC & Uber (2020) for total vehicle population and RTO data for EV population

1.1.1. Electric Vehicle Policies

So far, EV sales in India have been considerably lower compared to China, the European countries, and the USA (Gupta et al., 2018). In 2015, the Government of India released a scheme termed Faster Adoption and Manufacture of (Hybrid and) Electric Vehicles (*FAME-INDIA*, n.d.) that aimed to promote the manufacture and adoption of EVs throughout the country. It was to be implemented in two phases. The first phase of the scheme began in April 2015 and ended in March 2019 with several extensions. The second phase of the scheme got rolling from 1 April 2019 and ends on 31 March 2022 (Press Information Bureau, Government of India Cabinet, 2019). The main features of the scheme are as follows:

- A total investment of INR 10,000 crore has been earmarked to implement a number of measures.
- A demand-side subsidy of INR 10,000 per kWh of battery capacity is to be provided on certain EV sales. Buses can avail up to INR 20,000 per kWh of their battery capacity.
- The mentioned subsidy is only applicable to two-wheelers, four-wheelers, and buses used for passenger transport or registered for commercial purposes.
- To be eligible for the subsidy, EVs should have a certain percentage of components manufactured within India.

In addition, the government also launched a National E-Mobility Programme in 2018 under which the Energy Efficiency Services Limited will focus on setting up public charging infrastructure as well as demand creation of EVs.

Similarly, the Karnataka Electric Vehicle & Energy Storage Policy 2017 proposed a number of measures to enable the transition towards EVs in the future. Karnataka plans to attract investments close to INR 31,000 crore to develop manufacturing as well as research and development capabilities, leading to increased employment opportunities in this sector. Though EVs are becoming more affordable, the limited driving range offered by fully charged batteries poses a major barrier to their adoption. The policy measures discussed above also reflect on this problem while considering the setting up of charging infrastructure necessary to reduce range anxiety. The following are some of the steps being taken by the Karnataka government in this direction:

- Identify favourable locations for setting up charging stations and provide government land on lease/rent for the same
- Provide subsidy on investment for setting up the first 100 charging stations in the state
- Decide on a special tariff for EV charging service

These measures suggest that both central and state governments are actively trying to drive the automobile industry towards a cleaner and more sustainable future. With greater EV penetration, one can expect increased utilisation of grid electricity for charging. To accommodate increasing loads in the future, the existing grid may need an upgrade. The study has shown that localised and concerted charging behaviour can severely affect grid stability even at low EV adoption, Using renewable energy such as solar and wind can potentially reduce peak demand because of the collective charging behaviour of EV owners. Electricity generated using sunlight not only is renewable but also entails no pollutants or greenhouse gases during operation. Solar energy generated locally, such as from SRTPV systems, can be directed towards vehicle charging.

1.2. EV Charging Infrastructure

The Department of Heavy Industries (DHI) released guidelines for setting up public electric vehicle charging stations (EVCS) across India in 2018. Salient features of the guidelines include specifications on the necessary electrical equipment, the type of chargers, and the provision to facilitate online booking of the charging slots to EV owners. A public EV charging station today typically consists of, apart from the charging equipment, a data collection and processing facility (often provided by a third-party network service provider) and a mobile application to provide online booking as well as payment options to EV owners. The current mandated requirements for the public charging infrastructure provide a certain level of convenience to EV owners. The main components of the planned public EV charging business are shown schematically in Figure 1.

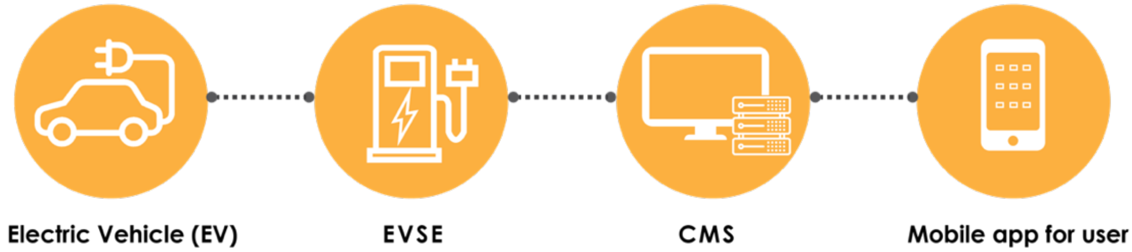


Figure 1: These are the main components of a public EV charging station. EVSE stands for "electric vehicle supply equipment", and CMS stands for "central monitoring system".

Main entities in the infrastructure:

1. EV charging service providers are companies that provide charging services to EV owners. They set up and maintain a number of charging stations. An EV charging network is a company that consolidates different charging service providers on a common platform where end-users can find information in one place. Some of the charging networks coming up in the country are Tata Power, Energy Efficiency Services Limited, Magenta Power, and Fortum.
2. Charge point operators (CPOs) are companies that operate a set of EV chargers. A number of services mainly related to data such as charger bookings and online payments are managed by the CPOs.
3. Electric vehicle supply equipment (EVSE) original equipment manufacturers (OEMs) are manufacturers of chargers and related equipment. Delta Electronics, ABB, Siemens, and Mass Tech are some of the companies operating in India. EVSE is defined by the DHI as follows: "it includes the electrical equipment external to the electric vehicle that provides a connection for an electric vehicle to a power source for charging and also is equipped with advanced features like smart metering, cellular capability, and network capability."
4. DISCOMs are electricity distribution companies that are responsible for setting up and maintaining electricity distribution networks to enable the uninterrupted supply of power to end-users. EV owners are their new customers.

1.3. Motivation for Solar-Based EV Charging

Air pollution is a major health hazard. Alarmingly, India has 21 of the 30 most air-polluted cities in the world (Regan, 2020). The transport sector in Indian cities is a major contributor to air pollution (contributes 40%–80%)—in the form of CO_2, NOx, and particulate matter. Hence, decarbonising the transport sector with the deployment of EVs is an important step towards the mitigation of air pollution. However, though EVs achieve zero tailpipe emissions, a cleaner mode of transport is realised only when they run on an eco-friendly source of energy: the renewables. As EVs will almost always be charged from an electrical grid, the renewable energy mix of the latter becomes important. The Indian electrical grid is currently dominated by coal, and it is the primary source of energy. However, recent analyses involving the life-cycle analysis of passenger cars in India have shown that even with the current Indian grid, battery EVs exhibit 19%–34% lower emissions over their lifetime compared to their gasoline counterparts (Bieker, 2021). The decarbonisation of the power sector needs to go hand-in-hand with vehicle electrification plans in the country.

Karnataka receives a large amount of solar radiation per day, ranging between 5.4 to 6.2 kWh/m^2. The state also enjoys between 240 to 300 sunny days per year. Thus, the total moderated solar potential of the state is estimated to be around 24.7 GW ("Karnataka Solar Policy 2014–2021," 2017). The Bangalore Electricity Supply Company (BESCOM) is responsible for power distribution in eight districts of Karnataka including Bengaluru. BESCOM aims to achieve a target of 1 GW of solar RTPV installation in its jurisdiction. The current installed capacity is around 107 MW, which is mainly driven by commercial users. Vehicle ownership and traffic congestion are extremely high in Bengaluru. The city has the highest number of two-wheelers and the second-highest number of four-wheelers in the country. The city is also second in the country in terms of fuel consumption for transportation. EV adoption, though currently sluggish, is expected to pick up in the coming years owing to the high purchasing power of people in the city and a number of upcoming EV-related start-ups.

2. Objectives of the Current Study

Key objectives of the pilot project:

- Develop an energy management approach to ensure optimal utilisation of the energy generated from an RTPV plant for charging EVs while considering EV owner's convenience, electricity pricing, and other relevant factors.
- Identify a suitable system architecture for direct or virtual integration of RTPV plants and EV chargers.
- Procure and commission an integrated solution for implementing the proposed system architecture.
- Guide policymaking for grid-connected solar- plus storage-based EV charging through a techno-economic analysis.

3. Existing System at the BESCOM Corporate Office

The BESCOM corporate office in Bengaluru houses two RTPV systems on two separate buildings. They are of capacities 50 and 40 kWp, as shown in Figure 2(a). There is also an in-house EV charging station—shown in Figure 2(c)—with four DC moderate and fast charging kiosks and one AC slow charging kiosk. BESCOM suggested considering a part of the 40 kWp capacity (equal to 20 kWp) installed on the Belaku Bhavana building for the study. In addition to the existing EV chargers, four more chargers of the following types have been installed in the same premises:

a. Three DC 001 (15 kW DC + 3.3 kW AC) Bharat chargers with a total load of 55 kW
b. One IS-17017 (25 kW CCS/CHAdeMO) charger with a total load of 25kW

The total load from the chargers, therefore, equals 80 kW. However, only one of the new DC 001 fast chargers has been used for the current study.

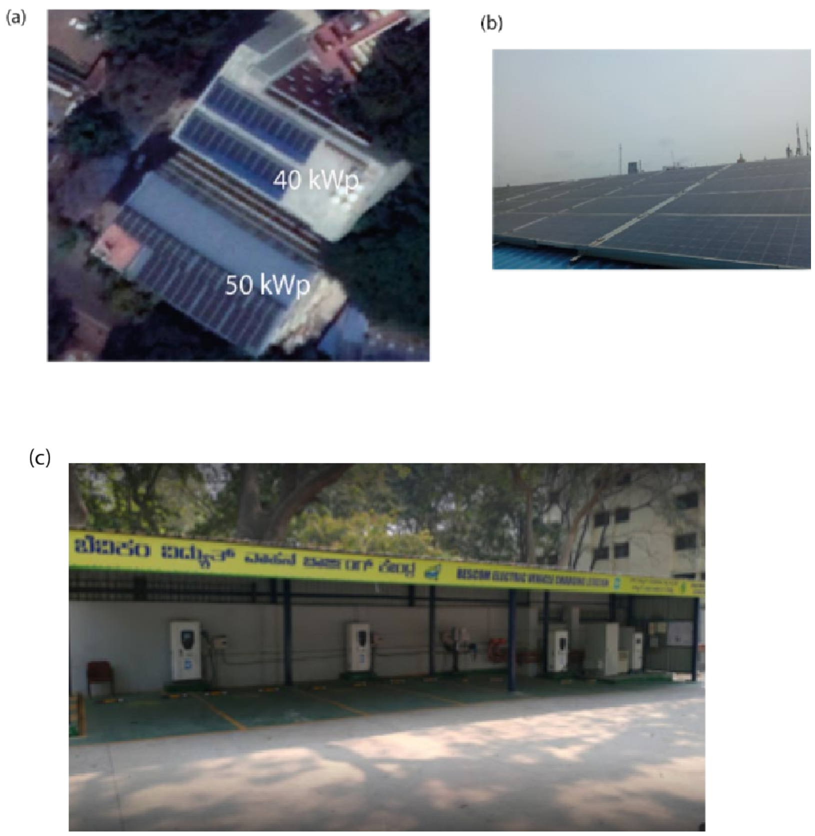


Figure 2: (a) Top view of the BESCOM Corporate Office premises in Bengaluru. The solar panels for both the 40 and 50 kWp systems of the two buildings are visible. (b) Enlarged view of the solar panels of the 40 kWp system and (c) EV charging station used for the pilot study

3.1 System Description

3.1.1 Solar RTPV System

As mentioned earlier, Belaku Bhavana has an installed capacity of 40 kWp for SRTPV. This system was chosen for the current study. The array of modules comprises two sets: one set is made of three and the other of four strings of serially connected modules. The three- and four-string sets are connected to an inverter of 20 and 25 kW rating, respectively. The two inverters are in turn connected to a computer for logging the power production data. This functionality is used in our proposed design in establishing a communication link between the EV charging station and the generation of solar energy, thereby enabling the opportunity for smart charging. The described RTPV system was commissioned on 15 March 2018. Therefore, considering a total lifetime of 25 years, the remaining life of the RTPV system is 24 years.

Figure 3 shows the total PV energy generated over the months of the year 2020. The data were generated by simulation using the PV Syst[1] program for the mentioned BESCOM site location. January showed the highest generation with a gradually decreasing trend through the months of June and July, which mainly represent the monsoon season. The energy generation subsequently increased over the following months. Such variations will affect grid utilisation; for example, a higher grid utilisation is expected during the months that show lower PV generation.

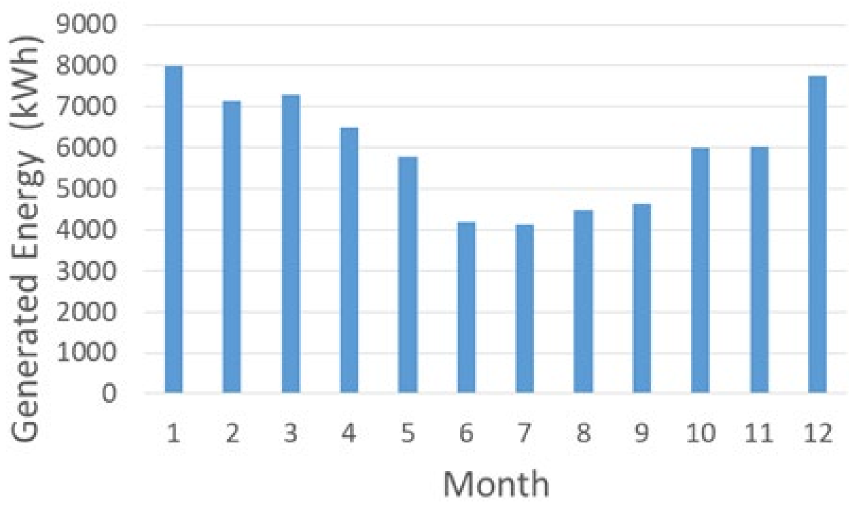


Figure 3: Monthly PV energy generation data from simulation for the 40 kWp RTPV system (for the year 2020)

3.1.2 Grid-Tied Inverters

Two grid-tied inverters, manufactured by SMA, were connected to two strings from the RTPV system. The inverters are of capacity 20 and 25 kW and are equipped with the maximum

[1] https://www.pvsyst.com/

power point tracking (MPPT) functionality, which enables them to operate in the maximum output range possible. With high efficiency of 98.4%, the inverters are considered suitable for large-scale industrial and commercial applications. Figure 4 shows the inverters installed at the site.

Figure 4: Existing string inverters of capacity 20 and 25 kW, connected to the 40 kWp RTPV system


STATION
ELECTRIC VEHICLE

4. Methodology

Considering the challenges associated with increasing RTPV penetration and the projected adoption of EVs, it is important to explore interventions that can address issues common to both. It may be noted that if the energy generated from RTPV is accompanied by a proportionate increase in local energy consumption, the challenges associated with power distribution network management can be resolved. Similarly, if the energy demand for charging EVs is met locally, it will avoid congestion on the existing power distribution infrastructure. Therefore, optimal utilisation of energy from RTPV for EV charging can prove to be an effective approach for addressing a diverse set of challenges in a synergistic manner. As generation from RTPV is intermittent, this approach shall require appropriate control strategies at EV charging stations. However, apart from the availability of solar generation, factors such as user preference and electricity pricing also need to be taken into account while developing control strategies. In addition, this approach also ensures that EVs consume clean energy generated from RTPV, adding to their emission mitigation potential.

4.1 System Design Details

The overall approach consisted of using a power conversion system (PCS) to interface with the solar panels and the battery bank to channel the combined energy for EV charging. The PCS was governed by an energy management system (EMS) to ensure maximum utilisation of solar energy. The main components of the design were as follows:

a. Power Conversion System

Delta Electronics proposed the design mainly comprising the mentioned PCS that can be programmed to prioritise EV charging based on solar energy generation. The PCS, RenE EVSE PowerSuite (125 kW), is an integrated system to power EV charging units from multiple generation sources such as solar, grid, and an optional battery backup. The unit has the provision to connect direct inputs from the PV system and battery units while providing an output for the charging station. With its advanced control systems and intelligence, the PCS ensures maximum power availability at the charging point irrespective of the source dynamics and grid outages. The PCS is equipped with connection accessories and a transformer set-up to provide ready-to-connect terminals to the EV charging system.

The system works in three modes:

- On-grid mode
- Off-grid mode
- Hybrid mode (denotes operation using the combination of solar, battery, and grid energies)

(a)

(b)

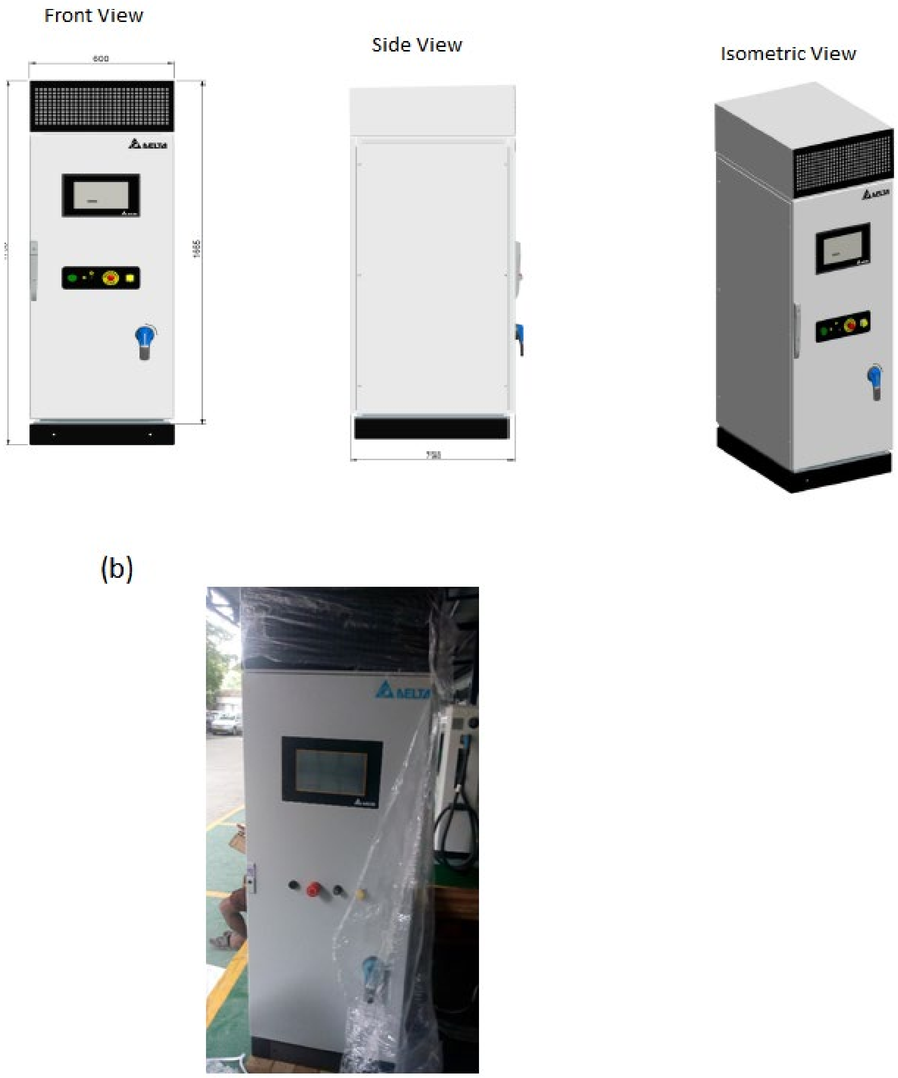


Figure 5: (a) Schematic of the PCS supplied by Delta Electronics and (b) snapshot of the system on-site

The PCS provides a bidirectional backup power solution. It has an inbuilt IGBT-based battery charger, which will charge the battery when the grid is available. Upon grid failure, the PCS operates in the islanded mode, where the grid contactor is opened, and the battery is discharged to provide power to the load. To ensure long life and withstand harsh Indian climatic conditions, it has high structural stability and is weather-resistant and termite-proof. Some of the important features are as follows:

- True bidirectional backup power solution
- No power de-rating in the operating temperature range (-10°C to 50°C)
- Rated output power kVA = kW
- Inbuilt IGBT-based battery charger
- No need for any additional external cooling arrangement
- External UPS is needed with a backup time of 5 min.
- Built-in climate protection, including humidity
- Outdoor unit, no need for inverter room or expensive containers

- Lightning surge protection is available at both DC and 3-phase AC sides of the inverter
- DC switch disconnector, manually operated
- Grid CB with remote operation and feedback
- Grid filter: LCL harmonic filter
- Main inverter: IGBT-based power stack including DC link capacitors
- HMI with remote access, generation data logging, and cloud compliance
- Weblogging with user-interactive data access
- Plug and play design
- Four isolated digital inputs and eight isolated digital outputs for external modules interface such as VCB and grid transformer monitoring relays

b. Battery Energy Storage

The set-up also uses a lithium-ion battery bank to power the EV charger. The two main uses of the battery bank are to maximise the utilisation of solar energy for charging and provide energy backup in the off-grid mode. The battery packs were also provided by Delta Electronics (see specifications in Table 3). The battery storage is directly connected to the PCS through a load break switch.

Table 3: Battery module specification

Parameter	**Value**
Nominal voltage	51.8 V
Nominal capacity	60 Ah
Nominal energy	3.1 kWh
Dimension (mm)	199 (W) x 187 (H) x 537 (L)
Weight	Approx. 24 kg
Cycle life (at 25 °C)	~3,000
Operating temperature	Charge: 0 °C to +45 °C Discharge: -20 °C to +45 °C
Discharge rate	Max. 4C (200 A)

(Source: Delta Electronics)

Table 3 shows that the energy capacity of each of the battery modules is 3.1 kWh. Fourteen such modules were connected in a series to form the bank (see Figure 6). Hence, the total energy capacity of the battery bank was 43.5 kWh. To ensure the safety and reliability of the battery module, it has a built-in cell monitoring unit (CMU) to manage the cell balance and collect individual cell temperature and voltage information. The CMU of each module communicates with the central battery management system (BMS) to protect battery modules from abnormal conditions, such as over-temperature, overcharging, or over-discharging. The built-in interface of communication allows remote monitoring and control by the EMS to perform functions of peak shaving, time-shifting, utility ancillary services, and so forth. Apart from lithium-ion, the PCS is also compatible with lead–acid batteries.

Figure 6: Snapshot of the (internal) battery bank showing 14 battery modules in series. The total energy capacity of the bank is 43.5 kWh.

Specifications of the entire battery bank:

Parameter	Value
Voltage	725 V
Total capacity (nominal)	43.5 kWh
Total current	60 Ah
Depth of discharge	80%

c. Energy Management System

The Delta Electronics EMS is an intelligent system that provides a grid dispatch interface and energy management for the BESS in particular. It is suitable for a system that consists of an energy storage system along with bidirectional EMS and an energy storage system with bidirectional DC/AC PCS. The EMS communicates with the BMS, PowerSuite controller, and EV controller and follows various algorithms to compute the output that needs to be performed. The generated set point commands the PowerSuite and BMS as per the application.

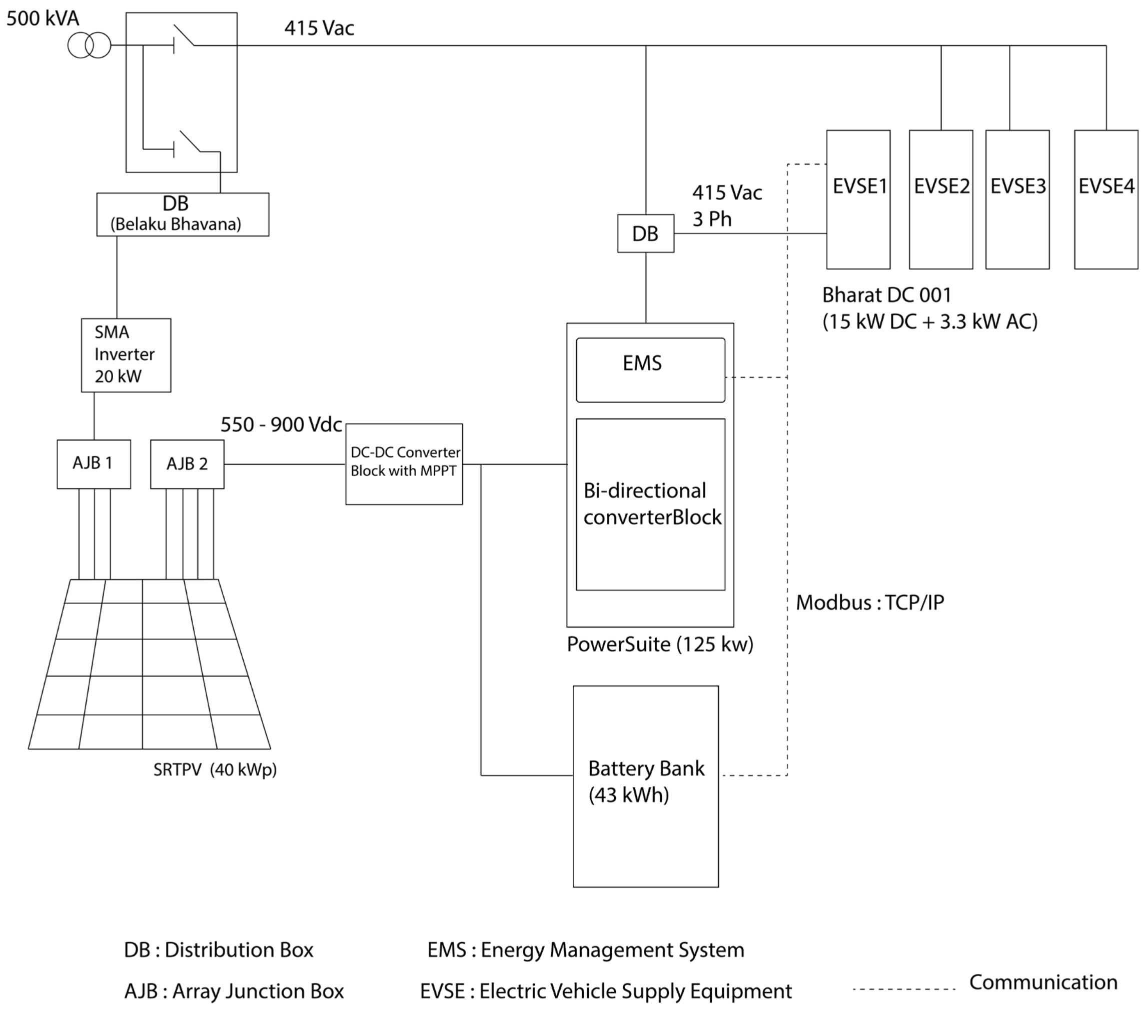
It supports the following functions:

- Power smoothing: To smoothen the fluctuations associated with renewable sources such as solar RTPV
- Energy time-shifting: To store excess energy for use during peak demand
- Backup application: In case of off-grid or power outages

It offers the following key features:

- Ten-inch touchscreen
- Modbus/CAN communication
- Event-based data logging
- Eight GB internal storage
- USB/FTP access
- Digital input and digital output
- Analogue input for sensor integration

(a)



(b)

(A: Bharat DC 001 charger, B: lithium-ion battery bank, C: MPPT block, D: transformer, E: PCS, and F: distribution box)

Figure 7: (a) Schematic showing PowerSuite-integrated architecture as implemented on-site (BESCOM corporate office premises) and (b) snapshot of the entire set-up on-site

4.2 Operation and Monitoring

The entire architecture is depicted in Figure 7(a) as a block diagram, and a snapshot of the equipment is shown in Figure 7(b). The deployed RTPV and energy storage based EV charging station can work in normal charging mode (both slow and fast depending on the user selection) and dynamic charging mode. In normal charging mode, the source of power to the EV charger is RTPV, the battery, and the grid. If the grid is not available, the PCS goes to the off-grid mode and RTPV and the battery will supply the EV charger. In the dynamic charging mode, the supply to the EV charger is proportional to the RTPV inputs.

RTPV is set as the primary source of power for the connected EV charger during normal and dynamic charging modes. If the PV power is deficient, the battery supplies the deficient power, ensuring its state of charge (SoC) is above its prescribed limit. If PV and the battery are unable to meet the EV demand, the grid supplies the remainder of the power based on availability. Similarly, when EV is unavailable, then the battery is charged with the in-situ PV power. If the battery is fully charged, then the excess power is fed to the grid. This priority is set as it ensures the energy produced on-site is consumed by the charger. This is explained in detail in the flowchart (Figure 8). In the flowchart, the upper and the lower SoC limits on the battery are 95% and 15%, respectively. Also, the starting and stopping of PV are through the MPPT converters.

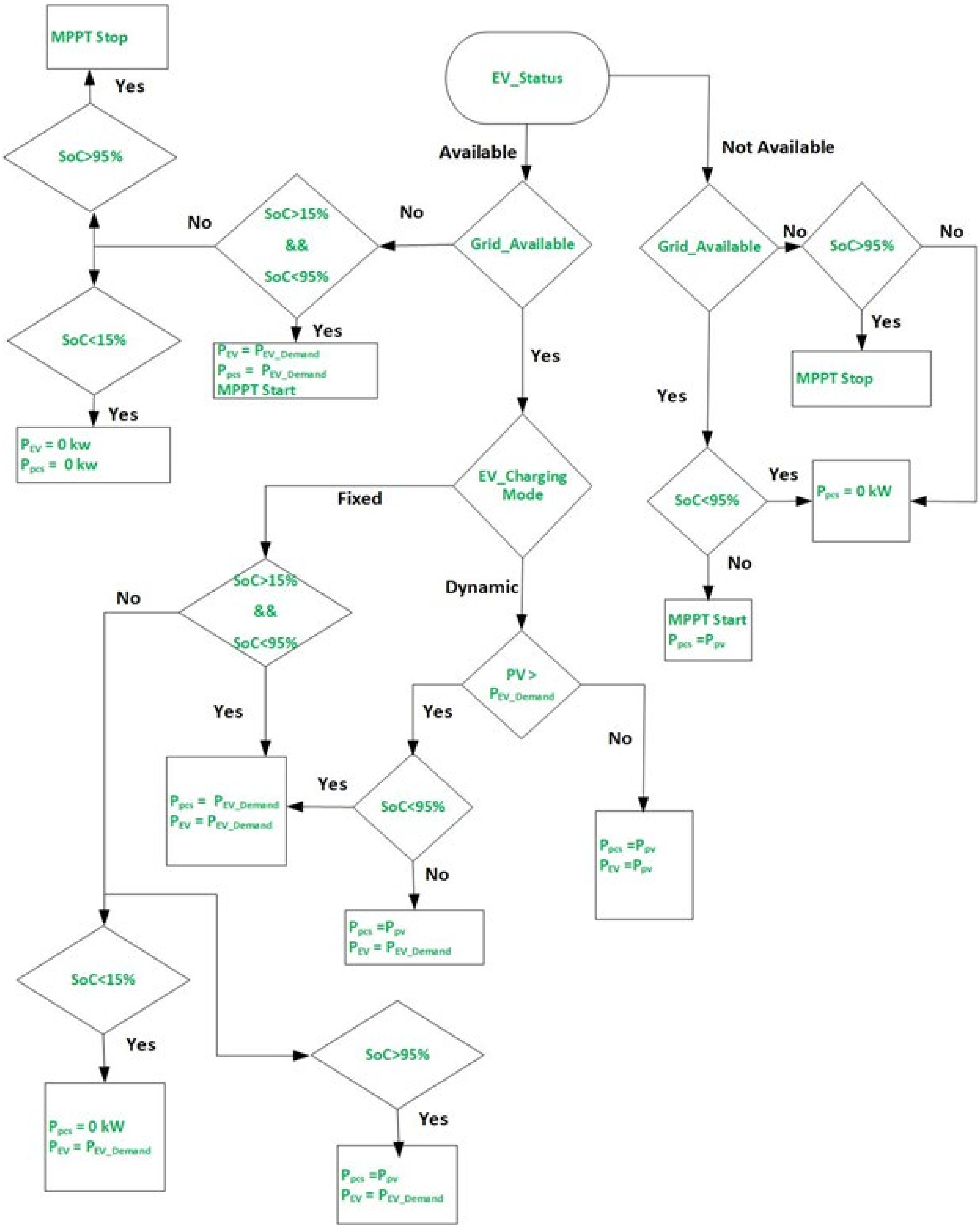


Figure 8: Source prioritisation algorithm for RTPV- and battery-coupled EV charger. Parameters' meaning – SoC: state of charge, P_{EV}: power demand from the EV, P_{PCS}: power delivered by the PCS, P_{PV}: power delivered/generated by the solar panels

The procedure for commissioning the set-up involved a site acceptance test performed by the implementer, Delta Electronics. The test involved verifying the energy management strategies (involving the smart charging feature) and testing the off-grid operation. The important parameters generated by the PCS were PV energy generation, battery SoC and energy, and the total PCS energy output to the chargers/grid. These parameters can be monitored in real-time via a remote connection to the PCS.

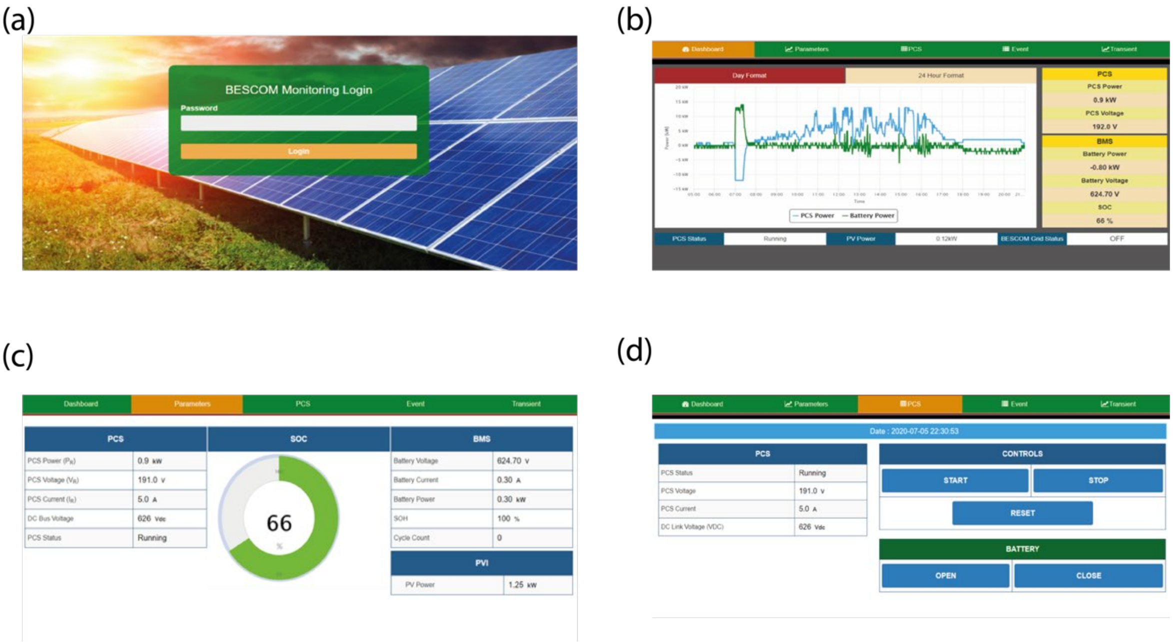


Figure 9: Snapshots of the user interface to the PCS for remote monitoring: (a) the user login page; (b) the dashboard showing the energy profiles related to PV generation, battery energy, and the total PCS energy as a function of time of day; (c) the display of certain parameters related to the PCS power and battery SoC; and (d) certain system-level controls in the same interface

Figure 9 shows a few snapshots of the remote monitoring interface that can be accessed from any computer. These are also the same pages that can be accessed directly on the human–machine interface of the PCS at the site. The dashboard page depicts different energy profiles (for PV generation and battery charge/discharge) over the present day. Other pages include a few more details on the relevant parameters including the battery's state of charge. These profiles, as a function of time of the day, can also be downloaded in a comma-separated values (CSV) format directly to the remote system for analysis. This feature helps in troubleshooting certain problems without actually visiting the site.

4.3 Data Collection

As noted above, the data of energy generation and other operations are logged in the PCS, which can be downloaded for analysis. Figures 10, 11, and 12 show data obtained during the site acceptance test performed on 1 September 2020. The plots shown are as follows:

- The PV generation (denoted as MPPT PV power) is represented by the orange-coloured plot.
- EVC power stands for the power consumed by the connected EV charger (black-coloured plot).
- PCS power represents the total power output from the PCS to the charger or the grid (blue plot).

The figure shows the energy consumption by the connected charger overlaid on the PV generation and battery charge/discharge profiles as a function of the time of day along the x-axis. A single Bharat DC 001 fast charger (15 kW) was connected to the PCS during the operation. Certain portions of Figure 10 are shown in the enlarged view in Figure 11 to show more details of the profiles.

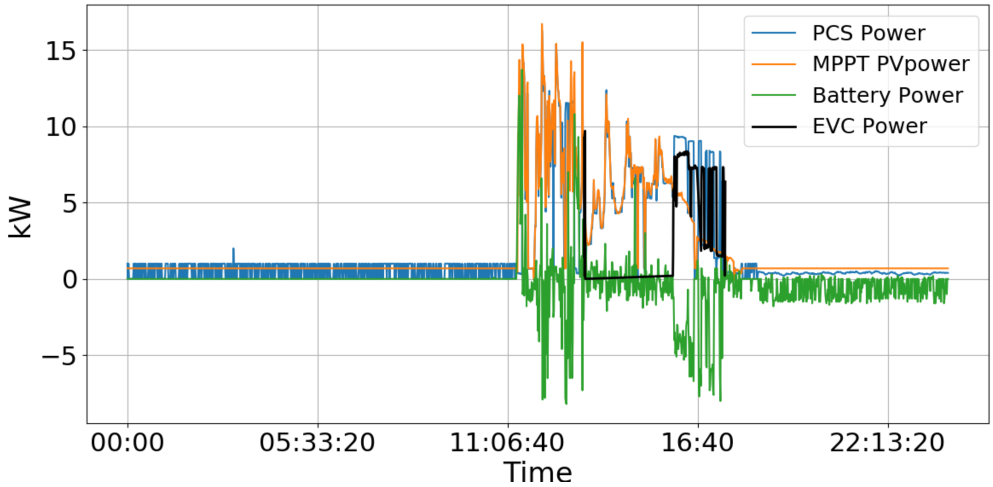


Figure 10: Energy and charging profiles logged in the PCS during its operation on 1 September 2020

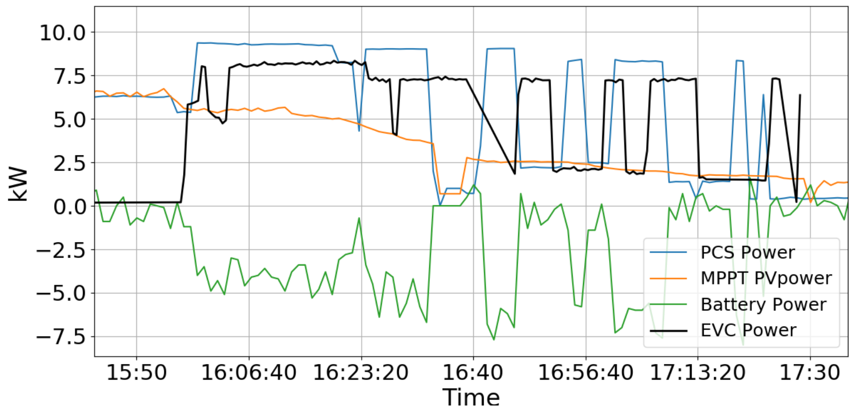


Figure 11: Enlarged version of Figure 10 during a specific time window

The data logged in the PCS are of the PCS power, PV generation (MPPT power), and battery power. The EV charger power profile was obtained from a different server separately. The horizontal segments of the black plot (EV charger demand) represent events of constant charging. The plot shows that the charging activity consisted of a number of short/intermittent charging events as the charger was connected/disconnected during the demonstration. The PCS power output, composed of the combined power from the battery and PV panels, is expected to follow the same trend as the EV charger demand. The energy/power flow can be understood from the schematic in Figure 13. The colours of the subcomponent blocks in the schematic match those of the corresponding plots in Figure 12.

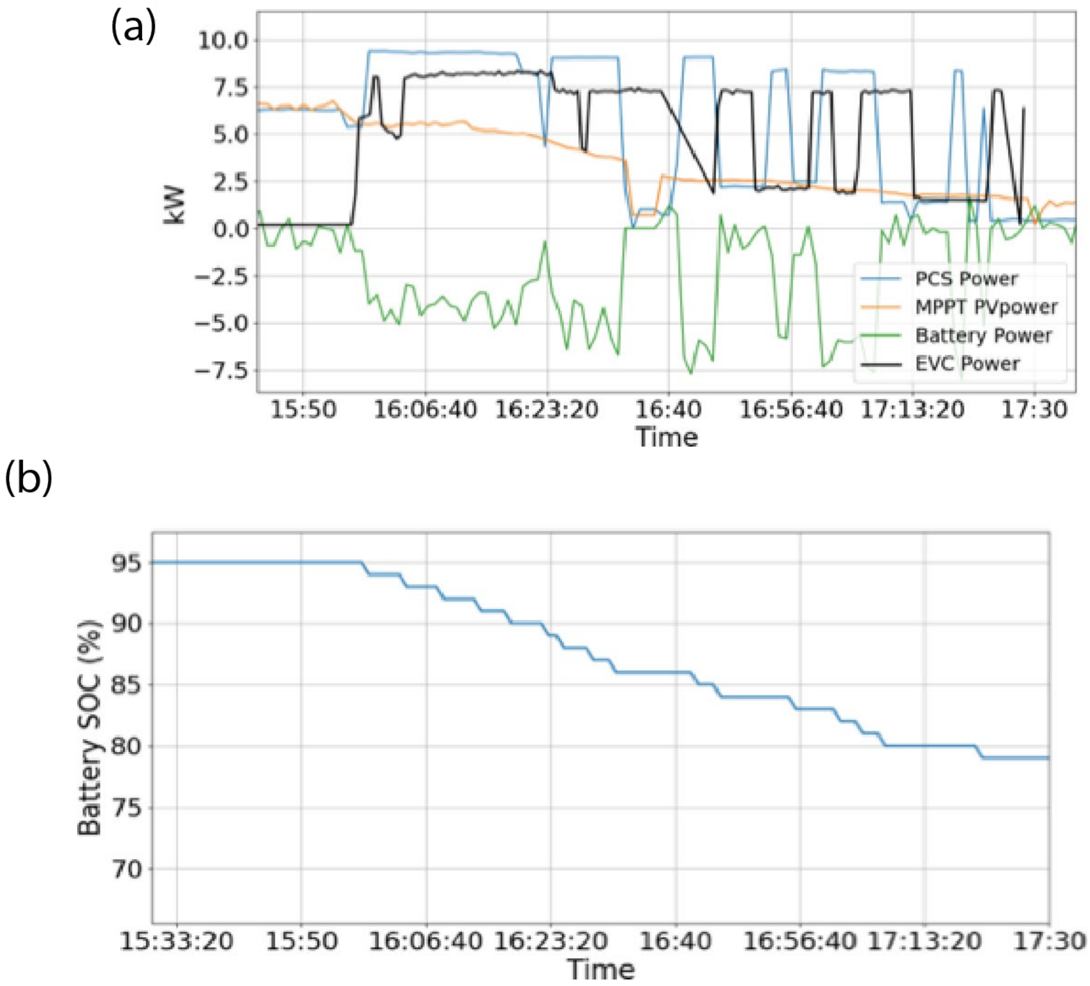


Figure 12: (a) The same graph as shown in Figure 11 and (b) battery SoC profile at the same time instants as in subfigure 12(a)

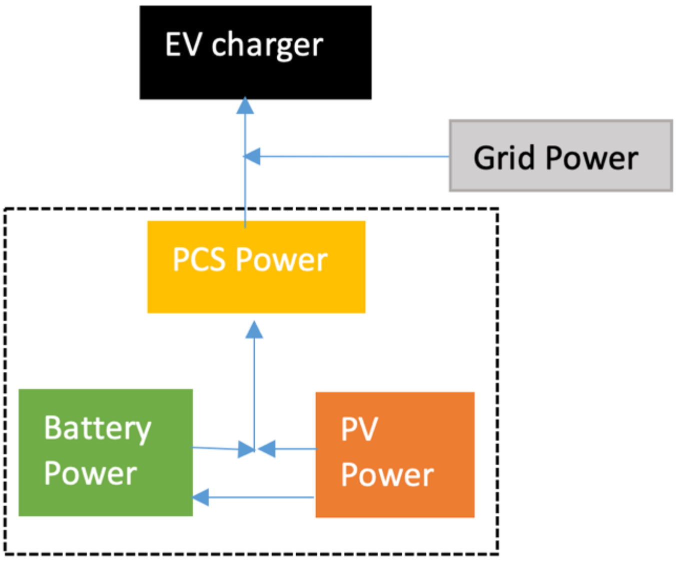


Figure 13: The schematic of the energy/power flow from various components to the EV charger

From the earlier discussions on the energy management strategies (Section 4.2) deployed in the set-up, it is clear that PV energy forms the first priority, followed by battery and then grid energy. This can be understood from the plots above. As seen in Figure 12(a), the PV power decreases continuously over the shown time period. However, the EV charger demands constant power (during charging events), denoted by horizontal sections of the plot. To compensate for the decreasing PV energy, the battery starts discharging accordingly so that the total power can follow the EV demand. The discharging of the battery is clearly shown by examining its SoC during the same period of time, as shown in Figure 12(b). The combined power of battery and PV, shown as the PCS power, then follows the EV demand.

Data sets on charging activities were examined over the months of September and October 2020 at the site. However, COVID-19-related restrictions have resulted in meagre charging events. In the next chapter, a detailed analysis of the techno-economics of using solar energy and solar plus storage is presented.

5. Techno-Economics of Grid-Tied RTPV Plus Storage-Based EV Charging

This chapter examines the cost implications of using solar RTPV systems as well as battery storage for charging EVs. As mentioned earlier, running EVs on grid electricity, which is predominantly powered by coal today, has minimal impact on addressing air pollution and climate change. Even though they reduce local CO_2 emissions, increasing the use of coal in the power plants ultimately tend to offset the reduction in CO_2 emissions on a global scale. Therefore, it is important to use renewables for EV charging.

The current scenario for EV charging infrastructure—depicted in Figure 14(a)—will need to shift to the architecture represented in Figure 14(b) and (c). In these scenarios, either the EV is being charged by the RTPV system alone or in combination with the RTPV system and an energy storage system. The subsequent sections will, therefore, estimate the cost implications of transitioning from the current scenario presented in Figure 14(a) to the scenarios presented in Figure 14(b) and (c) for public EV charging stations.

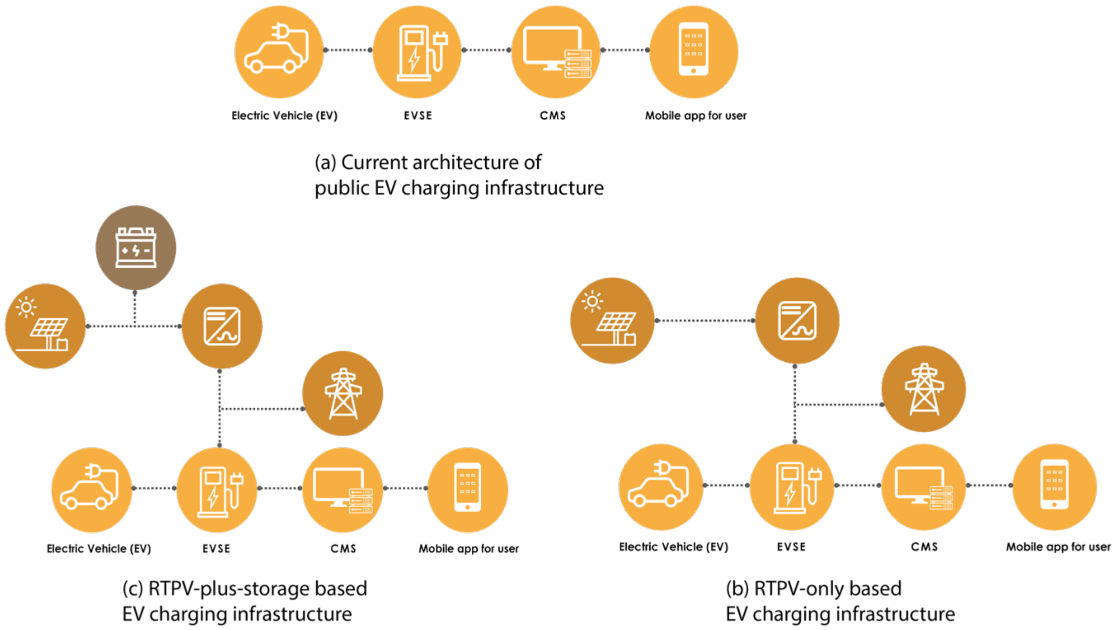


Figure 14: (a) Current system architecture of EV charging station, (b) EV charging with RTPV only, and (c) EV charging station with RTPV plus energy storage system

Figure 14(c) represents the most general case for the subsequent calculations. Both RTPV and the battery are DC systems and, therefore, will need a converter/inverter to combine with the AC electrical grid. Currently, the available EV chargers draw AC as input directly from the grid. The DC fast chargers will further convert AC to DC for charging the EV battery.

The BESS, as explained earlier, is primarily used to store excess energy generated from the PV for use when the sunlight is not available. This application is known as energy time-shifting and ensures maximum utilisation of the PV energy locally. Considering PV plus energy storage as a general case, we model the techno-economics of the entire system in the subsequent sections.

5.1 Modelling Framework

A simplified schematic (Figure 15) is used for arriving at the relevant metrics and equations for cost estimations. The main components are the PV block, the battery energy storage block (which also includes the PCS), EV supply equipment (chargers), and a distribution box (denoted as DB in the figure), which represents the point of interaction with the grid connection. The net-metering policy plays an important role in the cost calculations, as explained in subsequent sections. For analysis, the entire system inside the boundary named System C is further divided into subsystems A and B. System A consists of only the EV charging equipment, and System B represents the solar plus BESS power plant. These systems are discussed separately before addressing the cost calculations for the bigger integrated System C.

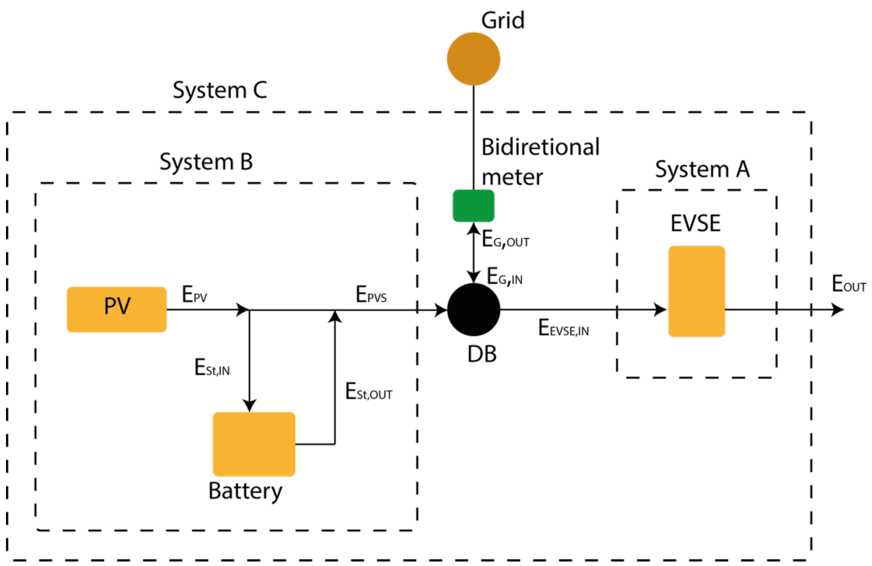


Figure 15: Block diagram used for the techno-economic modelling of solar- plus energy storage–based EV charging. DB represents the distribution box.

The explanation of the notations in Figure 15 are as follows:

Notation	Meaning
E_{PV}	Total energy output from the PV plant
$E_{St,IN}$	PV energy charging the storage system
$E_{St,OUT}$	Energy discharged from the storage system
E_{PVS}	Energy from the solar plus storage plant (System B)
DB	Distribution box
$E_{G,IN}$	Energy drawn from the grid
$E_{G,OUT}$	Excess PV energy being fed into the grid
$E_{EVSE,IN}$	Energy intake by the EVSE
E_{OUT}	Energy output from the entire system (System C) for charging EVs

The levelised cost of energy (LCOE) calculations are performed using the net present value method. The main idea of the metric is represented by Equation (1)

$$LCOE = \left(\frac{Net\ present\ value\ of\ capex\ and\ opex}{Total\ energy\ generated}\right)_{Over\ lifetime} \quad (1)$$

This formula has been extensively used in the literature related to an energy-generating asset such as a solar or wind power plant. The numerator consists of the capital and the operational costs to run the plant, which are discounted annually by a discount rate. All the cash flows are evaluated over the lifetime of the asset. The same idea (of LCOE) has been recently extended to assess the levelised costs for energy storage (Schmidt et al., 2019) as well as for EV charging (Borlaug et al., 2020). The corresponding terms used are levelised cost of energy storage (LCOS) and levelised cost of charging (LCOC). These metrics, with the following definitions, are used in the current analysis:

$$LCOS = \left(\frac{Net\ present\ value\ of\ capex\ and\ opex}{Total\ energy\ discharged}\right)_{Over\ lifetime} \quad (2)$$

$$LCOC = \left(\frac{Net\ present\ value\ of\ capex\ and\ opex}{Total\ energy\ output\ for\ charging}\right)_{Over\ lifetime} \quad (3)$$

In the following sections, Systems A (EVCS), B (solar plus storage plant), and C (integrated system) are analysed for the levelised cost calculations.

5.1.1 System A: EV Charging Station

An EV charging station can have a combination of fast and slow chargers. For the current study, a model EV charging station was used for all the relevant calculations. This model EVCS consisted of three slow/moderate chargers of capacity 15 kW and one fast charger of capacity 25 kW. The specifications are shown in Table 4.

Table 4: Model EVCS used in the following calculations

Charger Type	Charger Connections	No.
Fast	CCS and CHAdeMO (25 kW)	1
Slow/moderate	Bharat DC 001 (15 kW)	3

The cost parameters and the corresponding values for such a model EVCS are shown in Appendix A1. The LCOC is estimated using Equation (4). The summation is over the lifetime (denoted by N) of the EVSE. The capital costs include those of the chargers, power connection, and software for booking/payment and installation charges. The operation and maintenance costs exclude the rental on land, assuming the land is self-owned by the business. The denominator ($\sum E_{Chrg,n}$) represents the total energy output by the EVSE every year, summed over its lifetime for charging EVs, while C_{Grid} is the cost of electricity drawn from the electrical grid. An escalation rate of 3% per year in the tariff (denoted by e in the equation) is assumed.

As can be gauged from the equation, LCOC can be reduced by lowering the numerator (e.g., decreasing capital costs in the future) and increasing the energy output (i.e., the utilisation of the asset) over its lifetime. The term η_{EVSE} in Equation (4) represents the efficiency of the charger.

$$LCOC = \frac{CAPEX + \frac{\sum_{i=1}^{N} O\&M}{(1+r)^n} + C_{Grid}\frac{\sum_{n=1}^{N} E_{Chrg,n}(1+e)^n}{(1+r)^n}}{\frac{\sum_{n=1}^{N} \eta_{EVSE}\, E_{Chrg,n}}{(1+r)^n}} \quad (4)$$

where

$LCOC$	Levelised cost of charging
$CAPEX$	Capital expenditure
$O\&M$	Operations and maintenance cost
C_{Grid}	Cost of the grid electricity
$E_{Chrg,n}$	Yearly energy throughput for charging EVs
η_{EVSE}	Conversion efficiency of the chargers
e	Yearly escalation of the grid electricity cost
r	Discount rate

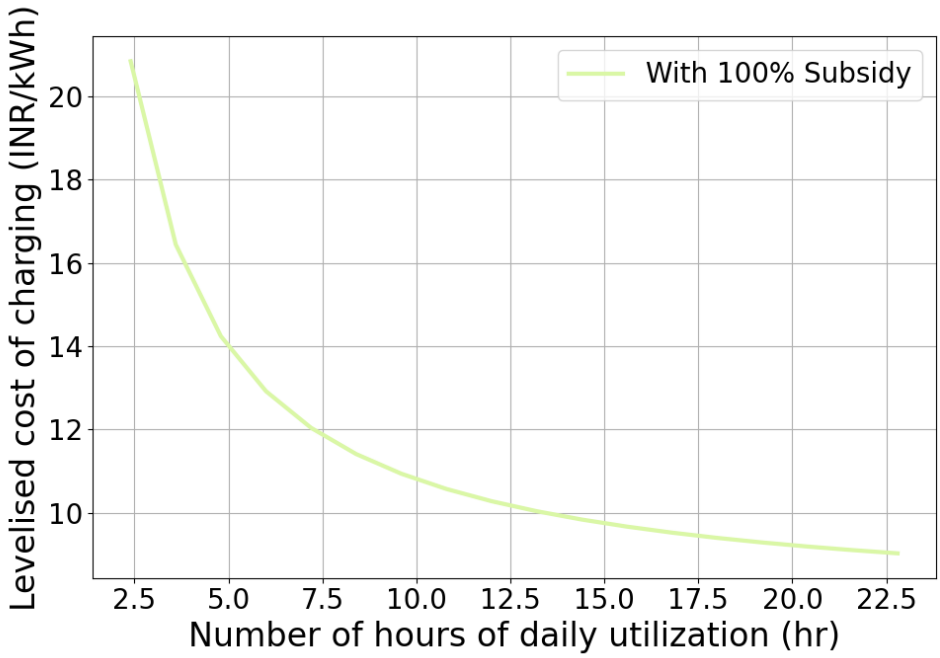


Figure 16: LCOC for the model EVCS as a function of daily utilisation of chargers. The x-axis denotes the number of hours of operation per day for each charger in the EVCS. It corresponds to 100% subsidy on the capex of EV chargers and for the grid electricity cost of INR 5/kWh (as in Karnataka).

$$\begin{pmatrix} Number\ of\ hours \\ of\ daily\ utilisation \end{pmatrix} = \begin{pmatrix} Number\ of\ hours\ all\ chargers\ in\ Table\ 4 \\ are\ utilised\ in\ a\ day \end{pmatrix}$$

The utilisation of the model EVCS (i.e., of the constituting chargers) is estimated as the number of hours in a day every charger (listed in Table 4) is utilised, though a more realistic case involves disparity in their usage pattern (one charger may be used more than the other). A uniform utilisation of all the chargers is assumed in the current calculations for simplicity. As seen from Figure 16, the LCOC varies non-linearly with the daily usage of the chargers. The values, in fact, increase faster at lower utilisation (below 6 hours). As per the figure, the LCOC comes to ~INR 18.5/kWh (with 100% subsidy) at the model EVCS for a daily operation of 3 hours, which is expected in the current scenario of low EV adoption in the country.

5.1.2 Effect of Subsidies

Another important factor in bringing down costs is the role of subsidies. The Department of Heavy Industries (DHI), in their call for proposal in 2019 ("Expression of Interest Inviting Proposals for Availing Incentives under Fame India Scheme Phase II For Deployment of EV Charging Infrastructure within Cities," 2019), planned to install 1,000 EV charging stations (with around 6,000 chargers) across major cities in India through the provision of demand-side incentives. The department classified the EVCS into the following categories for disbursing subsidies (verbatim from the document):

Category A: Charging stations established at public places for commercial purpose to charge EVs and are available to any individual without any restrictions for charging their vehicles and are installed as per the Ministry of Power notification dated 14 December 2018 and its amendment thereof (e.g., EVCS established in municipal parking lots, petrol stations, streets, malls, and market complexes).

Category B: Charging stations established within the premises of a state or central government office complex, government hospitals/clinics/dispensaries, government educational institutions, or any other public office for non-commercial use (e.g., EVCS established in Udyog Bhawan, Shram Shakti Bhawan, and the PSU Office Complex).

Category C: Charging stations established within the semi-restricted premises for commercial or non-commercial purpose for charging EVs. However, said chargers are also available to any individual for charging EVs without any restrictions. (e.g., EVCS established for taxi aggregators for charging of taxies and cooperative housing societies).

Accordingly, the maximum subsidies (under the FAME II scheme) are as follows:

i. Category A: 70% of the cost of the EVSE
ii. Category B: 100% of the cost of the EVSE
iii. Category C: 50% of the cost of the EVSE

It must also be noted that the cost of upstream electrical infrastructure (e.g., transformers) will not be covered by the incentives above.

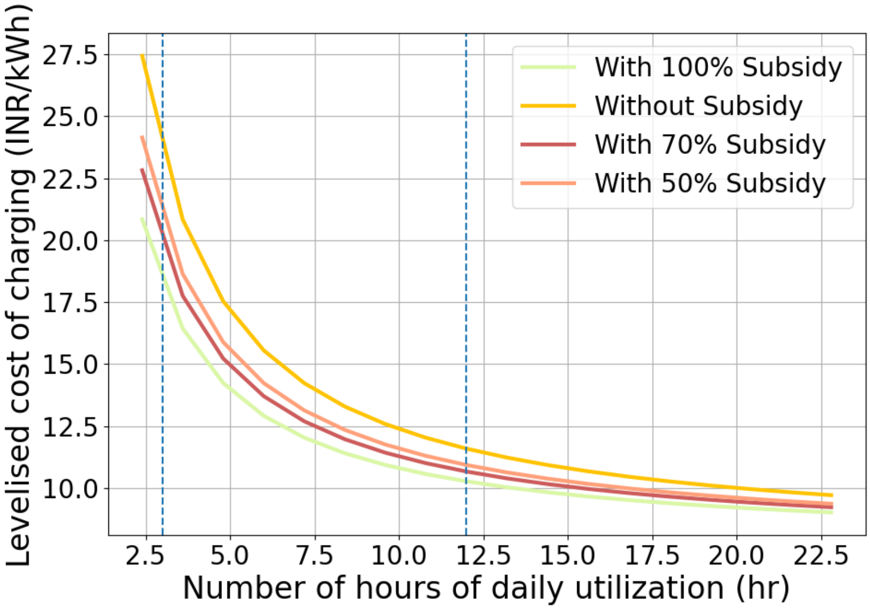


Figure 17: The effect of subsidies on the LCOC at the model EVCS (cost of grid electricity = INR 5/kWh for all cases)

Figure 17 examines the effect of the percentages of subsidies on the LCOC for the model EVCS (Table 4). It can be seen that the contribution of incentives towards cost reduction is relatively more pronounced at lower utilisation, which is currently the case across the country owing to the low adoption of EVs. Consider the case of 3 hours per day of daily utilisation; the LCOC without subsidy is close to INR 24.5/kWh. With 100% subsidy, it comes down by 32% to ~INR 18.5/kWh. In a scenario where the utilisation is 12 hours per day, the corresponding reduction is 11%. Overall, there is a substantial reduction in the LCOC with the addition of subsidies.

5.1.3 Effect of Grid Electricity Cost

EV owners are the new customers of DISCOMs. To promote EV adoption in the country, most of the states and union territories have set specific electricity rates for EV charging, both for private as well as business purposes. Figure 18 shows the tariffs across different states in the country as per the recent report by Das and Tyagi (Das & Tyagi, 2020). The tariffs hover between INR 4 to INR 7. Among the states, Uttar Pradesh, Maharashtra, and Kerala are the only states to have time-of-day tariffs for EV charging. Karnataka has a time-independent tariff of INR 5 per kWh for residential consumers (owning EVs) and EV charging businesses. For residential consumption, the EV owner has to set up a separate meter to benefit from the mentioned rate. EV charging stations will bear demand charges of INR 70/kVA/month for low tension (LT) and INR 200/kVA/month for high tension (HT) consumers.

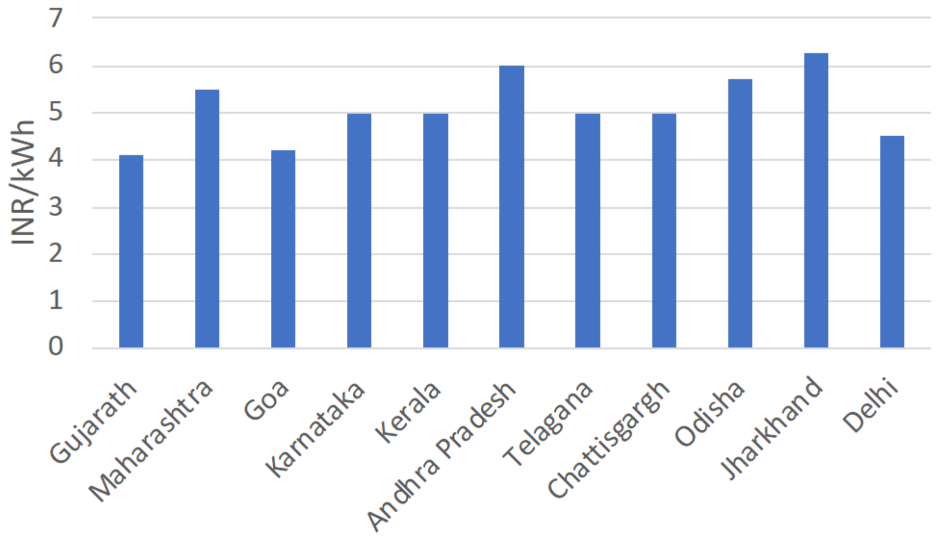


Figure 18: Electricity tariffs for EV charging across select states in the country. Source: Das & Tyagi, 2020)

Figure 19 shows the variation of LCOC at different grid electricity costs. It is assumed in these calculations that the electricity cost remains the same through the 10-year lifetime period. In the figure, the bottom-most curve has an electricity cost of INR 4/kWh. This cost increases by INR 0.5 with subsequent curves on the top. From the plot, it can be seen that the differences between the LCOC curves are equal to the differences in the electricity costs at any point on the x-axis. This is as expected since all other costs in the calculations are the same for all the curves in the figure.

The effect of lower tariffs is evident in how quickly they can help attain a certain desired LCOC. For example, an LCOC of INR 9/kWh is reached with 11.5 hours of daily utilisation at the tariff of INR 4/kWh, whereas a tariff of INR 5/kWh for the same LCOC is attained with 15.5 hours of utilisation.

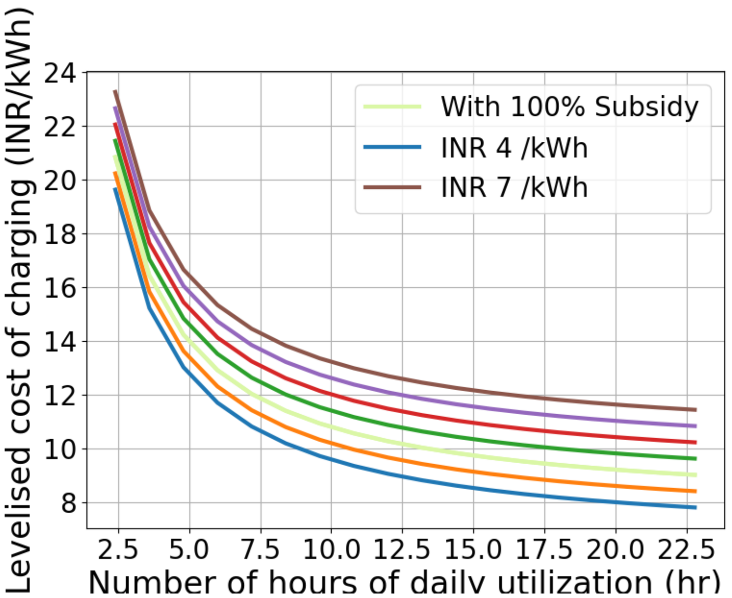


Figure 19: The effect of different electricity tariffs on LCOC (with 100% subsidy on EVSE). The bottom-most and the top-most figures correspond to INR 4 and 7/kWh, respectively. The intermediate curves represent increments by INR 0.5/kWh from the bottom to the top.

5.2 Grid-Tied Solar- Plus Storage-Based EV Charging (Systems B and C)

Here, we consider System C where energy is sourced from a solar plus energy storage system, and the entire system is grid-tied. We derive the necessary equation, by energy balance, to estimate the levelised cost of grid-tied solar- plus energy storage–based EVCS by extending Pawel's methodology (Pawel, 2014).

Consider System C in Figure 15. Let $LCOC_{Tot}$denote the LCOC from System C. By definition,

$$LCOC_{Tot} = \frac{\sum C_{PV} + \sum C_{St} + \sum C_{EVSE}}{\sum E_{OUT}} \quad (5)$$

where C_{PV}, C_{St}, and C_{EVSE} are the combined capital and operations and maintenance (O&M) costs of the PV plant, energy storage, and the EVSE, respectively. E_{OUT} is the total energy output from the EVCS to the EV chargers (Figure 15). The discounting factors in these terms are implicit.

The energy output E_{OUT} from the EVSE is related to the input energy $E_{EVSE,IN}$ as

$$E_{OUT} = \eta_{EVSE} E_{EVSE,IN} \quad (6)$$

where η_{EVSE} is the energy conversion efficiency of the EV charger.

Consider the energy flow across the distribution box in Figure 15. The input energy $E_{EVSE,IN}$ can be further written as

$$E_{EVSE,IN} = E_{PVS} + E_{G,IN} - E_{G,OUT} \quad (7)$$

Hence, using Equations (7) and (6) in (5), we get

$$LCOC_{Tot} = \frac{\sum C_{PV} + \sum C_{St} + \sum C_{EVSE}}{\eta_{EVSE} \sum (E_{PVS} + E_{G,IN} - E_{G,OUT})} \quad (8)$$

$$LCOC_{Tot} = \frac{\sum C_{PV} + \sum C_{St} + \sum C_{EVSE}}{\eta_{EVSE} \sum E_{PVS} \left(1 + \left(\frac{E_{G,IN} - E_{G,OUT}}{E_{PVS}}\right)\right)} \quad (9)$$

Introducing a new term ξ as

$$\xi = \frac{E_{G,IN} - E_{G,OUT}}{E_{PVS}} \quad (10)$$

$E_{G,OUT}$ and $E_{G,IN}$ are the energy flowing out and into System C from the grid, that is, it is the net energy imported from the grid, which eventually is used by the chargers at the EVCS.

Equation (9) can be further simplified to represent a sum of the levelised costs of the power plant energy and charging from the EVSE as:

$$LCOC_{Tot} = \frac{\sum C_{PV} + \sum C_{St} + \sum C_{EVSE}}{\eta_{EVSE} \sum E_{PVS}(1 + \xi)}$$

$$LCOC_{Tot} = \frac{\sum C_{PV} + \sum C_{St}}{\eta_{EVSE} \sum E_{PVS}(1+\xi)} + \frac{\sum C_{EVSE}}{\sum E_{OUT}}$$

Assuming a uniform input from the grid throughout its operation,

$$LCOC_{Tot} = \frac{1}{\eta_{EVSE}(1+\xi)} \left\{ \frac{\sum C_{PV} + \sum C_{St}}{\sum E_{PVS}} \right\} + \frac{\sum C_{EVSE}}{\sum E_{OUT}}$$

$$LCOC_{Tot} = \frac{LCOE_{PP}}{\eta_{EVSE}(1+\xi)} + LCOC_{EVSE} \qquad (11)$$

The $LCOC$ is estimated for the EVSE alone (System A), whereas $LCOE_{PP}$ is estimated for the solar plus storage power plant (System B). Hence, calculating $LCOC_{Tot}$ entails estimating $LCOE_{PP}$ and $LCOC_{EVSE}$ (for EVSE only). While the latter has been modelled (as shown earlier), the methodology to calculate $LCOE_{PP}$ is shown in the following section.

5.2.1 Estimating Solar Plus Storage LCOE (System B)

To model the solar plus storage power plant, the framework by Pawel (Pawel, 2014) was adopted. The levelised cost of energy of the power plant (denoted as $LCOE_{PP}$) is given as follows:

$$LCOE_{PP} = LCOE_{PV} \frac{1}{[1 - A(1-\eta)]} + LCOS \frac{\eta A}{[1 - A(1-\eta)]} \qquad (12)$$

$$A = \frac{E_{IN.St}}{E^{*}_{OUT,PV}} \qquad (13)$$

The notations denote the following:

$LCOE_{PV}$	Levelised cost of the energy generation by the solar plant
$LCOS$	Levelised cost of (energy) storage
A	Utilisation of solar energy for storage
η	Round-trip efficiency of the battery/storage

Utilisation A is the fraction of energy generated from the solar plant that goes into storage. For example, assume that the 40 kWp solar plant generates energy for an average of 5 hours per day. The total energy generated per day is equal to 200 kWh. If the energy storage of size 40 kWh performs one cycle per day, that is, it will charge and discharge 40 kWh per day, the utilisation is 40/200 = 20%. With two cycles per day, its utilisation is 80/200 = 40% and so on. Equation (12) shows that the total LCOE of the solar plus storage power plant (denoted as $LCOE_{PP}$) is obtained as a sum of the levelised costs of the solar panel system and the energy storage after multiplying each term with certain weighing factors. Hence, in the following sections, the calculations of the levelised costs for the solar RTPV and the energy storage are elucidated.

5.2.2 Estimating the LCOE of an RTPV System

The cost parameters for modelling an SRTPV system are given in Appendix A2. The cost calculations to estimate the LCOE is well established in the literature. It is given by the formula in Equation (14).

$$LCOE_{PV} = \frac{CAPEX + \frac{O\&M}{\sum_{n=1}^{N}(1+r)^n}}{\frac{\sum_{n=1}^{N} E_{Gen}\,(1-Deg)^n}{\sum_{n=1}^{N}(1+r)^n}} \quad (14)$$

The notations in Equation (14) denote the following:

$LCOE_{PV}$	Levelised cost of energy generation by the PV plant
$CAPEX$	Capital expenditure of the plant
$O\&M$	Operation and maintenance cost
$Deg.$	Annual degradation of the PV plant
E_{Gen}	Annual energy generation
r	Discount rate

The LCOE of solar RTPV system calculated in two scenarios: with BESS and without BESS, yields two different values. With BESS, the LCOE is of lower value (INR 3.6 /kWh as seen later) since an inverter is excluded from the calculations. This is because the PCU, that comes with the BESS does the DC to AC conversion. In the case of without BESS, the LCOE is higher (INR 4.6 /kWh) owing to the additional inverter cost.

5.2.3 Estimating the Levelised Cost of Storage

The levelised cost of storage (LCOS) is estimated as per the work of Schmidt et al. (2019). Equation (15) is used for its calculation, with the explanation of the terms given below.

$$LCOS = \frac{CAPEX + \frac{O\&M}{\sum_{n=1}^{N}(1+r)^n} + \frac{ChargingCost}{\sum_{n=1}^{N}(1+r)^n} - \frac{V_{Residual}}{(1+r)^{N+1}}}{C_{cyc,tot} \times \eta \times DOD \times C_{nom} \times \sum_{n=1}^{N} \frac{(1-Deg.)^n}{(1+r)^n}} \quad (15)$$

The battery of interest in this analysis is lithium-ion. A power conversion unit (PCU) is used to interface the battery (a DC system) with the grid (which is an AC-based system). Hence, the cost of the PCU will be concomitant with that of a lithium-ion battery bank. Another important piece of equipment that will accompany the battery bank is the EMS. Both the PCU and the EMS have been described in detail in the previous chapters. The cost details are tabulated in Appendix A3.

$LCOS$	Levelised cost of storage
$CAPEX$	Capital cost of battery + PCU + EMS
$O\&M$	Operation and maintenance cost of battery + PCU
$ChargingCost$	Cost of charging the battery from the grid
$V_{Residual}$	End of life cost of battery + PCU
DOD	Depth of discharge
r	Discount rate
$Deg.$	Annual degradation of the battery
C_{nom}	Nominal battery capacity
$C_{cyc,tot}$	Total number of cycles per year of the battery

The degradation of the battery during cycling affects the total energy input/output by the battery and hence its utilisation. The details of incorporating the degradation effects are discussed in more detail in Appendix A3.

Table 5: Important assumptions and considerations in all the following calculations

System-level details		
SL No.	**Comment**	**Value (if applicable)**
1	Size of the RTPV	40 kWp
	Total energy generation by RTPV per day (assuming 5 hours of average generation time)	200 kWh/day
2	Battery bank capacity	40 kWh
3	Life of EV chargers	10 years
4	Cost of electricity from the grid	• Variable cost = INR 5/kWh • Fixed cost = INR 200/kW/month (assuming HT connection) • An escalation of 3% annually is assumed for the variable cost
Assumptions		
1	An EV charging station is modelled as per the specifications listed in Table 4.	
2	The total lifetime for the calculations is considered to be 25 years, which is the life of the RTPV system.	
3	Replacements of chargers, battery banks, and inverters are considered in the calculations.	
4	The capital cost of chargers is excluded for the first-time installation because of a 100% subsidy. Following replacements include full capital costs of the same.	
5	No escalation in the fixed costs of the grid is assumed over the 25-year period.	
6	The land cost for the EVCS is excluded in all the calculations above.	

As seen from Equation (12), the $LCOE_{PP}$ is a function of multiple parameters such as the size of the PV system, size of the battery bank and its utilisation (number of cycles, etc.), and its round-trip efficiency. To simplify the calculations, the sizes of the PV plant and the battery bank (energy storage) are kept fixed. The SRTPV of size 40 kW and a lithium-ion battery bank of size 40 kWh are assumed for all the following calculations.

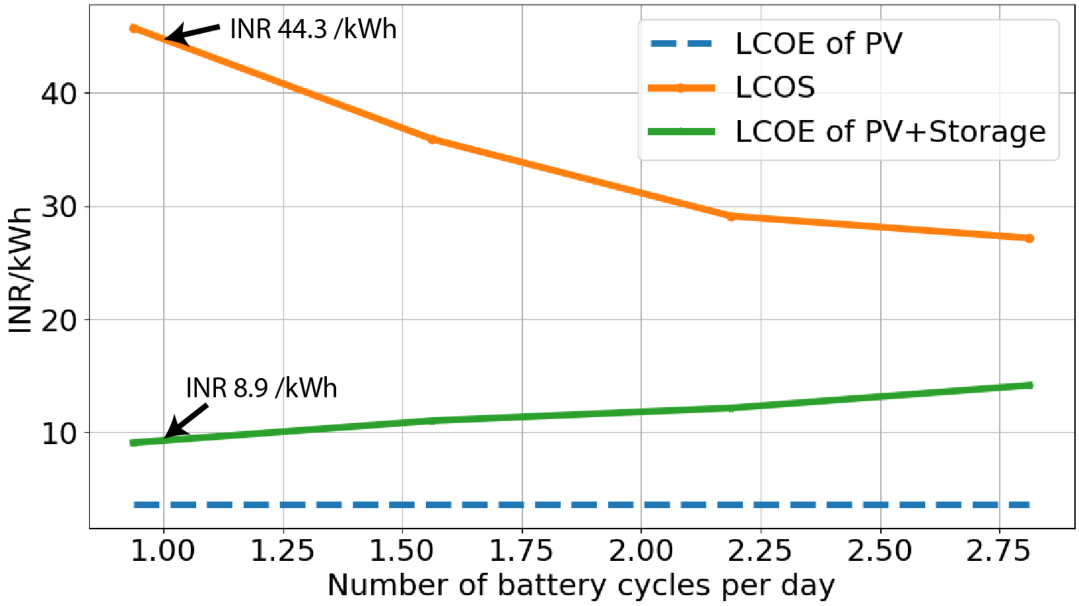


Figure 20: Levelised cost of solar PV plus storage plant along with the same for subcomponents (PV only and storage only) as a function of battery utilisation. The PV plant and storage sizes are maintained constant throughout the calculations. The values highlighted with arrows are used in the analysis in the subsequent sections.

Figure 20 shows the variation of the levelised cost of the energy output from the solar plus storage plant (System B in Figure 15) at different degrees of battery utilisation. From the plot, the following observations can be made:

- With the increasing number of battery cycles per day (i.e., its daily utilisation), the levelised cost of storage (LCOS) decreased. However, with increasing battery utilisation, the levelised cost of energy (LCOE) from the entire plant increased since more of the generated energy was now channelled through the battery, which is an expensive component.
- The LCOE of the plant varied from INR 8.9 /kWh at one cycle per day to ~INR 12.2/kWh at 2.5 cycles per day, while the LCOS varied from ~INR 44.3/kWh to ~INR 28/kWh for the mentioned daily cycles.

5.2.4 Estimating the Total LCOC (System C)

As the LCOE of the solar plus energy storage power plant has been estimated, the same for the entire EVCS (System C in Figure 15) can be obtained from Equation (11). This total LCOC—denoted as $LCOC_{Tot}$ in Equation (11)—for the model EVCS (Table 4) is shown in the plot of Figure 21. The black line plot shows the variation in the total $LCOC_{Tot}$ as a function of daily hours of operation of the EVCS, with a mix of energy from the solar plus storage plant and the grid. Owing to net metering, it is assumed that all the energy generated by the RTPV is consumed for EV charging (i.e., no excess energy is exported to the grid at the end of a billing cycle). The contribution of energies from PV plus storage and the grid is shown in the bar graph. The total size of the PV system in the analysis is equal to 40 kWp. Hence, with 5 hours of average daily operation, the total PV energy generated is 200 kWh (blue-coloured bar in the plot). The orange bars show an increasing contribution from the grid at the cost of INR 5/kWh.

Note that all the calculations involving RTPV and storage systems presented here consider replacements of the relevant components such as chargers, inverters, and the battery bank because their lifetimes are lower than that of the RTPV plant (taken to be 25 years). Such replacements were not considered for calculations in Section 4.1.1, where the EV chargers relied solely on the grid. While the EV chargers are being replaced, even though a 100% subsidy was considered at the start, subsequent replacement costs involve the full cost of the chargers.

As the contribution from the grid increases, the overall levelised cost decreases owing to the increased use of the cheaper grid energy over the relatively expensive energy from the solar plus storage plant. From Figure 21, it can be seen that the overall LCOC from the EVCS connected to the grid-tied solar plus storage plant varies from around INR 22/kWh at 2.8 hours of operation (where the EVCS functions only on the RTPV energy) to INR 10/kWh at 24 hours of daily operation. Midway, at 12 hours of daily operation, the cost equals ~INR 11.7/kWh. The battery is assumed to perform one cycle per day in this analysis.

Extending the analysis above to the grid-tied solar RTPV EVCS (i.e., without energy storage) is fairly easy and is shown in Figure 22. For the same energy mix from RTPV and the grid as in the previous case, the $LCOC_{Tot}$ is lower, as expected, than that when the energy storage is included (Figure 21). $LCOC_{Tot}$ for the case of RTPV only with the grid varies from INR 17/kWh (at 2.8 hours of daily operation) to about INR 9.4/kWh (12 hours of operation). Figure 23 compares the levelised cost of all three systems: grid-tied EVCS with PV plus storage, with PV only, and EVCS only.

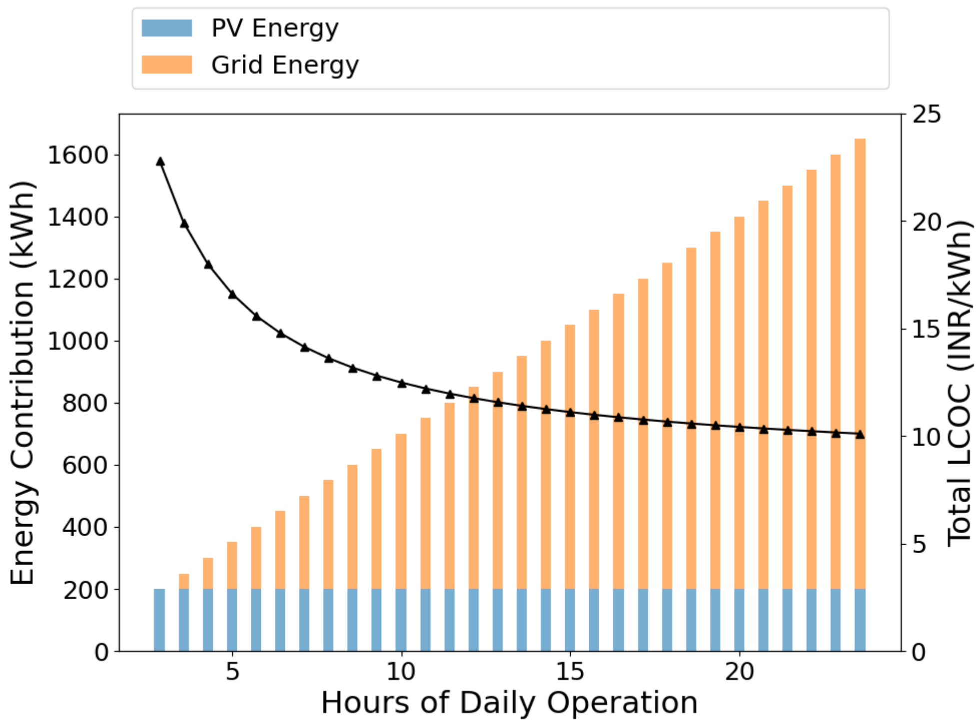


Figure 21: The variation of the total levelised cost of charging (LCOC) of the model EVCS connected to a solar plus storage system (line plot). The bar graphs represent the mix of solar and grid energies.

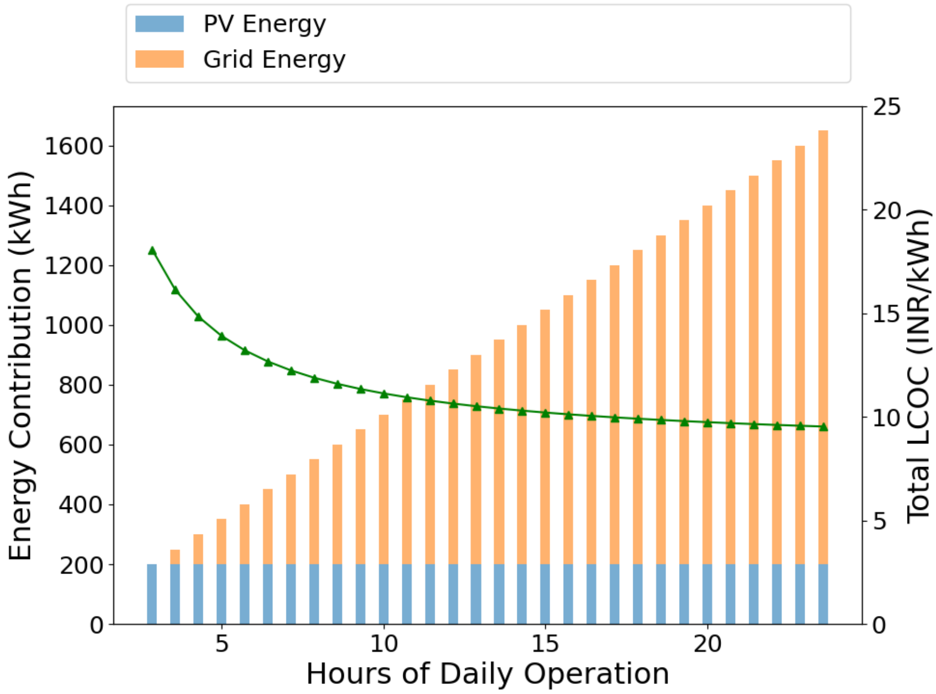


Figure 22: The variation of the levelised cost of charging (LCOC) of EVCS connected to an RTPV system without energy storage (line plot). The bar graphs represent the mix of solar and grid energies.

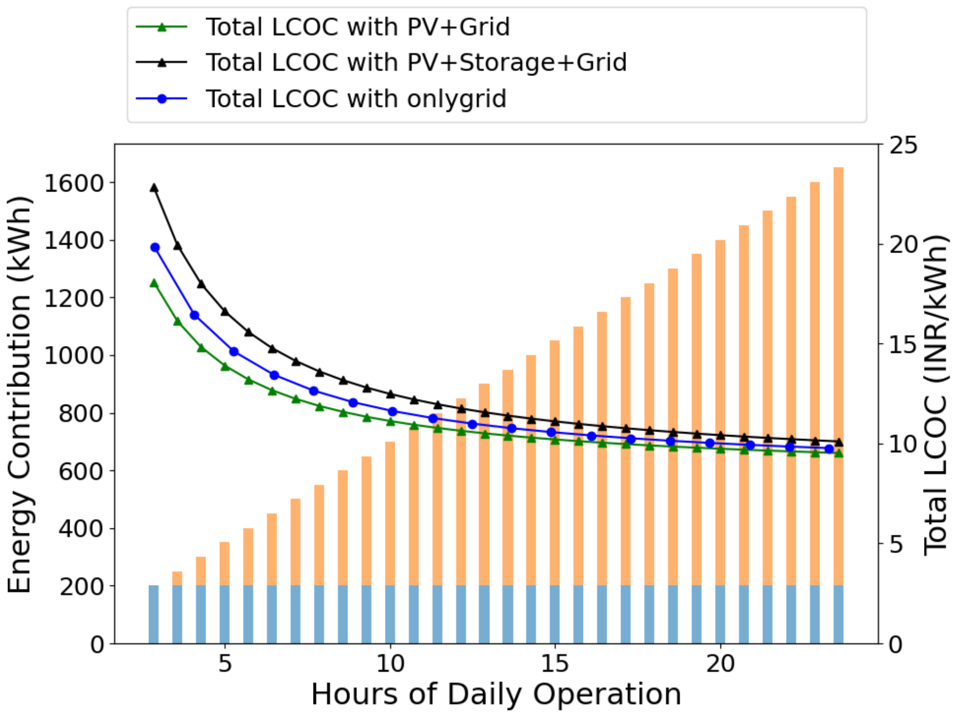


Figure 23: The comparison of the levelised cost of charging (LCOC) from the model EVCS for the three cases: with RTPV only, with RTPV and energy storage, and just the EVCS alone. All the calculations involve replacements of components (chargers and inverters) over a time of 25 years (= RTPV life). The bar graphs show energy contributions from the grid (orange) and the RTPV system (blue).

Figure 23 shows how the $LCOC_{Tot}$ of the model EVCS varies when connected to an RTPV or RTPV plus energy storage system as a function of hours of operation per day. The EVCS relying only on the grid energy is taken to be the baseline case. All the important considerations and assumptions in these calculations are listed in Table 5. The levelised cost upon using RTPV energy (green line plot in the figure) in the total energy mix is slightly lowered compared to the baseline case of the EVCS relying completely on the grid. It can be seen that the difference in $LCOC_{Tot}$ estimated for the two cases—PV plus grid and grid only—are not much (less than 0.01%). This can be attributed to the fact that the LCOE of PV estimated here is only slightly lower (by INR 0.5/kWh) than the electricity cost from the grid, which is reflected as the cost difference between the two cases.

Furthermore, the difference in the $LCOC_{Tot}$ decreased with a higher mix of the grid energy as expected. Note that (as emphasised earlier) the arguments and analysis being presented here assume operation under the net-metering policy, which ensures complete utilisation of the generated solar energy even when there is a mismatch between generation and consumption/charging events. The LCOC for the EVCS depending on RTPV plus storage plus grid is seen to be higher than that of the grid only scenario (blue curve) at all times of operation, as expected, owing to the additional cost of energy storage. This difference is higher at lower utilisation. The difference is ~INR 4/kWh at 2.8 hours of daily utilisation, while it is ~INR 0.5/kWh at 20 hours of daily utilisation. This reduced difference at higher utilisation between the $LCOC_{Tot}$ of the two cases is because of the increasing contribution of the cheaper grid energy since there is no change in the utilisation/operation of the solar plus storage power plant. Further discussions on understanding the results vis-à-vis the contributing subsystems are presented in the following section.

5.3 Understanding the Results

To further understand the results, consider the schematic shown in Figure 24. The costs of the subcomponents of the composite system are shown in the figure. The LCOS is the costliest contributor (INR 44.3/kWh), which represents the value of the portion of the total PV-generated energy channelled through the battery bank. However, some portion of the generated energy is directly used from PV for charging. This combined levelised cost of the solar plus storage power plant is given by the $LCOE_{PP}$, which in a certain scenario (of one battery cycle per day) is equal to INR 8.9/kWh (the mentioned values are denoted in Figure 20). As expected, this value lies between LCOS and LCOE of the PV plant.

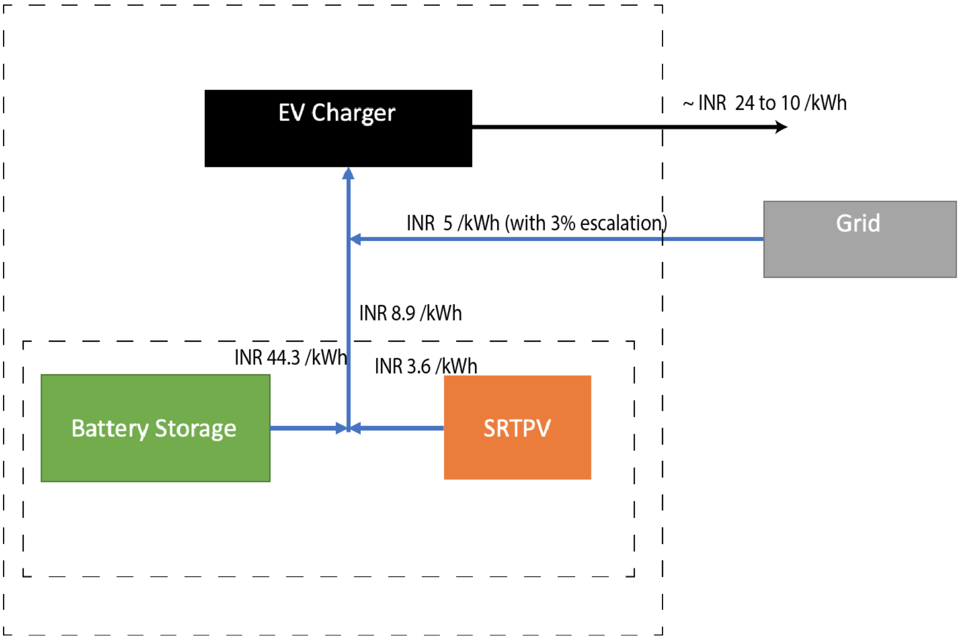


Figure 24: Schematic showing the costs associated with different subcomponents of the grid-connected RTPV–based EVCS

The EV charger has two sources of energy, one from the power plant at INR 8.9/kWh and the other from the grid at INR 5/kWh. Energies from both sources are used in certain proportions during the EVCS operation. The bar graphs from Figures 21 through 23 represent the different mix of the two. In scenarios where the EVCS relies more on the power plant energy than the grid, the LCOC is substantially high. As the contribution from the grid energy increases, owing to its lower cost, the $LCOE_{Tot}$ becomes less expensive. It should also be noted that the lowering in $LCOE_{Tot}$ is also partly driven by the increased utilisation of the EVCS over higher hours of operation.

At all times of the operation, the $LCOC_{Tot}$ for RTPV plus grid is only slightly lower than that of the grid-only scenario. The reason for this is the fact that energy from the PV plant is marginally less expensive (INR 4.6/kWh) compared to that from the grid. The current electricity tariff of INR 5/kWh applied in the BESCOM jurisdiction is a subsidised cost that can be rolled back in the future. Since the analysis shows that an RTPV (with net metering) system can compete with such a low tariff, the same (RTPV with net metering) provides the best-case scenario for reducing the operational cost for an EVCS. Scenarios without net metering will generally increase costs, owing to net PV energy being exported to the grid, and require further detailed analysis involving daily load and generation profiles, which are not considered in this study.

Finally, it should be noted how the $LCOC_{Tot}$ varies with the size and utilisation of PV and the battery bank. When the PV plant size is increased, its levelised cost decreases, thereby lowering the overall $LCOC_{Tot.}$ Upon increasing the utilisation of the battery (e.g., by increasing the number of daily cycles) or increasing the battery size, the $LCOC_{Tot}$ increases, as the battery bank is the costliest component in the set-up. Reducing the battery size shifts the entire black curve downward, in the direction of the blue curve, which represents the grid-only scenario. When the battery size is completely discounted in the analysis, retaining the grid-tied RTPV system, the black curve will eventually overlap with the green curve, which is shown in Figure 23.

5.4 Conclusion and Recommendations

The current chapter (Chapter 5) analysed the commercial aspects of using grid-connected solar rooftop PV with and without a battery energy storage system (BESS) to power an EV charging station (EVCS). A helpful parameter used in the study to estimate the economic benefits of using solar energy and BESS for EV charging is the levelised cost of charging (LCOC; also referred to as the cost of charging), which considers all the costs incurred over the lifetime of the assets. The estimated cost of charging from the solar-powered charging station was determined by estimating the contributions from the solar plus storage power plant and the stand-alone charging station separately and then combining them.

The key points of the analysis are as follows:

1. The cost of charging service from a charging station depends on the utilisation of the chargers, as expected. Lower utilisation increases the cost of charging service offered by the station.
2. Subsidy on chargers (as currently offered by the DHI) can considerably reduce the charging cost, especially at lower charger utilisation. However, future investments related to replacing the chargers at their end of life will increase this cost in the long term.
3. The levelised cost of energy generated by the solar plus storage power plant (denoted as $LCOE_{PP}$) is strongly influenced by the utilisation of the battery storage. Higher utilisation of battery storage increased the cost of energy from the power plant as more energy was channelled through the expensive battery bank.
4. The levelised cost of EV charging service from an EVCS was evaluated and compared with three cases: a baseline case where the EVCS is solely reliant on grid electricity and two other cases where it is connected to RTPV and RTPV plus energy storage systems. An RTPV system size of 40 kWp was considered for this analysis. The EVCS connected to the RTPV under the net-metering policy served as the best-case scenario with the lowest LCOC. This is predominantly because RTPV energy is less expensive than grid energy (grid electricity cost is at INR 5/kWh, which will possibly increase to INR 7 or more in the future).
5. A battery storage capacity equal to 40 kWh was considered for the analysis, which stored approximately 16% of the total daily solar energy (on average) generated. The cost of upstream electricity for the cases of the grid only, PV only, and PV plus BESS are INR 5, INR 4.6, and INR 8.9, respectively. Hence, including BESS increased the cost of the PV electricity by INR 4.3/kWh.
6. The net-metering policy plays an important role in lowering the $LCOE_{PP}$ and $LCOE_{PV,}$ which otherwise would increase owing to the mismatch between energy generation and consumption. With net metering, the excess energy generated that is fed to the grid during the day can be thought of as being drawn back, free of cost, as long as no net energy is exchanged with the grid during the billing cycle. Hence, under this policy, the grid acts as a “virtual battery” that helps to time-shift excess energy during the day back to the night for consumption. Without this facility, the levelised cost would increase whenever the cheaper PV energy is fed to the grid because of the mismatch with the consumption. Hence, it is recommended that an EVCS with a solar RTPV system should also use this policy for cost savings.

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7. Appendix A1

EVSE costs considered in the analysis

Table 6: EVSE costs considered for the techno-economic analysis for the model EVCS

	Cost (INR)		Comment
	Capital Cost		
CCS & CHAdeMO	15,00,000 x 1		CCS, combined charging system, is a standard followed in Europe. CHAdeMO, CHArge de Mode, is a charging standard that originated in Japan. Power capability: 25 kW per piece
Bharat DC 001	2,40,000 x 3		Power capability: 15 kW per piece
New power connection	15,00,000		
Civil works	2,50,000		
Software	50,000		
	Operational Cost		
Staff salary	2,40,000		Annual cost
Software cost	INR 1.5 per kWh charged		Subscription model
Land rent	0		Assumed government or self-owned land is used
Retail electricity from the grid cost	INR 4 to 7 per kWh		
	Technical/other details		
Life of the EVSE	10 years		
Discount rate	10%		
Loan interest rate	12.5 %		
Equity: Debt	30:70		

8. Appendix A2

Solar RTPV costs in the analysis

Table 7: Solar RTPV costs considered in the techno-economic analysis

Component/parameters	Cost
Module	INR 24,000/kWp
Inverter	INR 6,000/kWp
Mounting structure	INR 6,000/kWp
Balance of the system (cabling and auxiliaries)	INR 9,000/kWp
O&M	0.5% of capex
Degradation rate of PV modules	0.8 % (annually)
Insurance cost	0.5% of capex
Plant life	25 years
Discount rate	10%
Loan interest rate	12.5%
Equity: Debt	30:70
Life of inverters	13 years

9. Appendix A3

Energy storage model (lithium-ion battery)

The degradation of the battery during cycling affects the total energy input/output by the battery and hence its utilisation. Taking this into account, the energy input to the battery on a daily basis is modelled as

$$E_{IN,St}(day) = n_{cyc,day} C_{nom}\ DOD\ (1 - deg.)^{n_{cyc,tot}-1} \quad (16)$$

where

$$n_{cyc,day} = \frac{AE^{*}_{OUT,PV}}{C_{nom} DOD} \quad (17)$$

$n_{cyc,day}$: Number of cycles per day

$n_{cyc,tot}$: Total number of cycles

C_{nom}: Nominal capacity of the storage system

$deg.$: Degradation per cycle

DOD: Depth of discharge

In Equation (17), the utilisation A is estimated on a daily basis.

The cyclic degradation deg is calculated as follows:

$$C_{nom}\ (1 - deg)^{CycLife} = 80\% C_{nom}$$

$$deg = 1 - 0.8^{\frac{1}{CycleLife}} \quad (18)$$

$CycLife$ is the total number of charge/discharge cycles in its lifetime

The life in years of energy storage can then be estimated based on the number of cycles per day and the total number of cycles.

Table 8: Cost and other related parameters for a lithium-ion battery bank in the techno-economic analysis

Variable	Value
Capital cost of the battery bank	USD 350/kWh (battery)
Capital cost of PCS	INR14,000/kW
Capital cost of EMS	INR 3,00,000
O&M	1% of capex
VResidual	10% of capex
Charging cost	Scenario-based
Cycles per year	Scenario-based
Total number of cycles	3,000
DOD	80%
Total life of PCU	15 years
Total life of the battery in a year	Depends on cycles per year
Discount rate	10%
Loan interest rate	12.5%
Equity: Debt	30:70

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