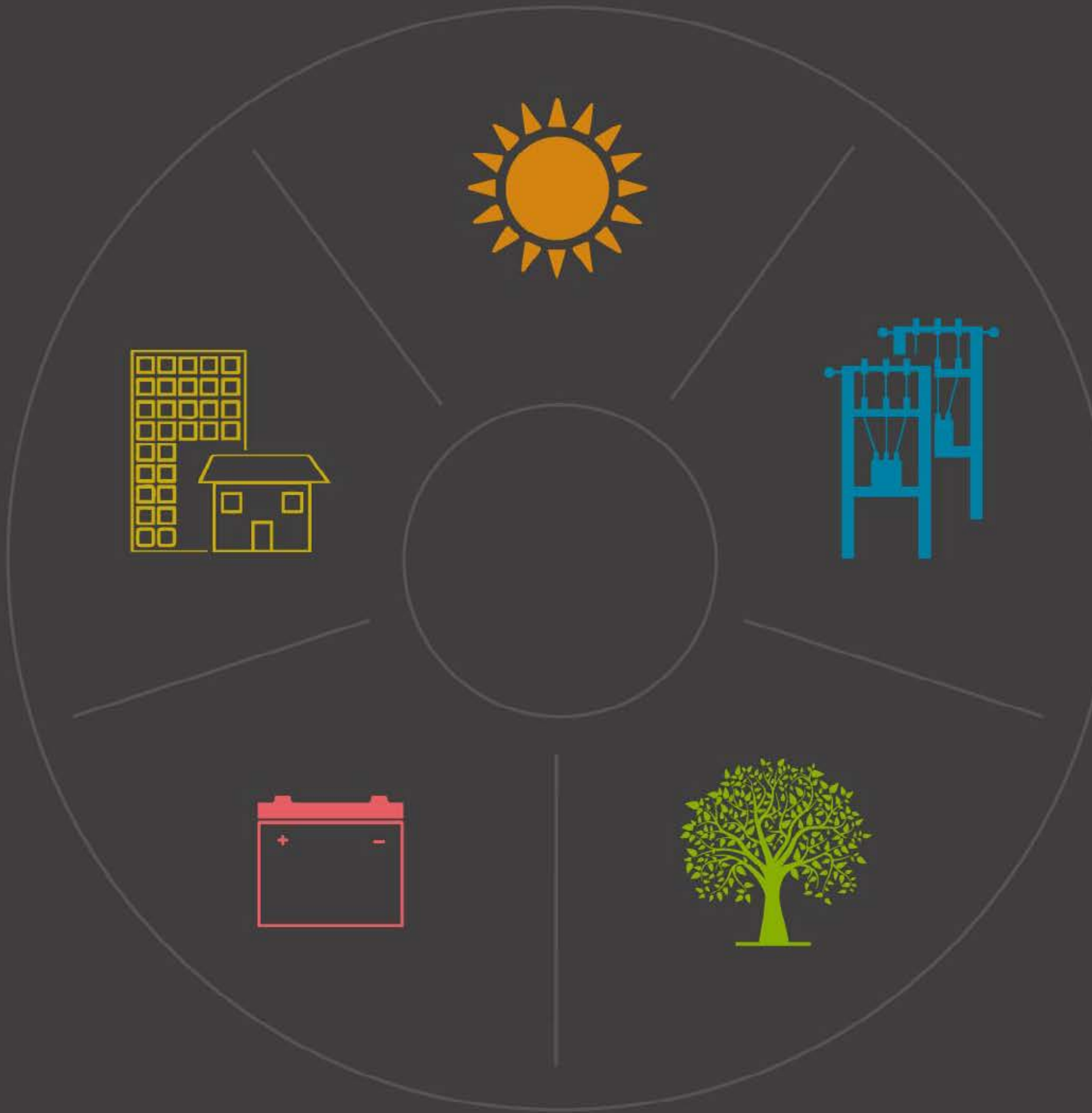
A Study on Energy Sourcing and Storage

Auroville, India



Energy Sourcing Study

Study on electricity sourcing and storage

Auroville, India

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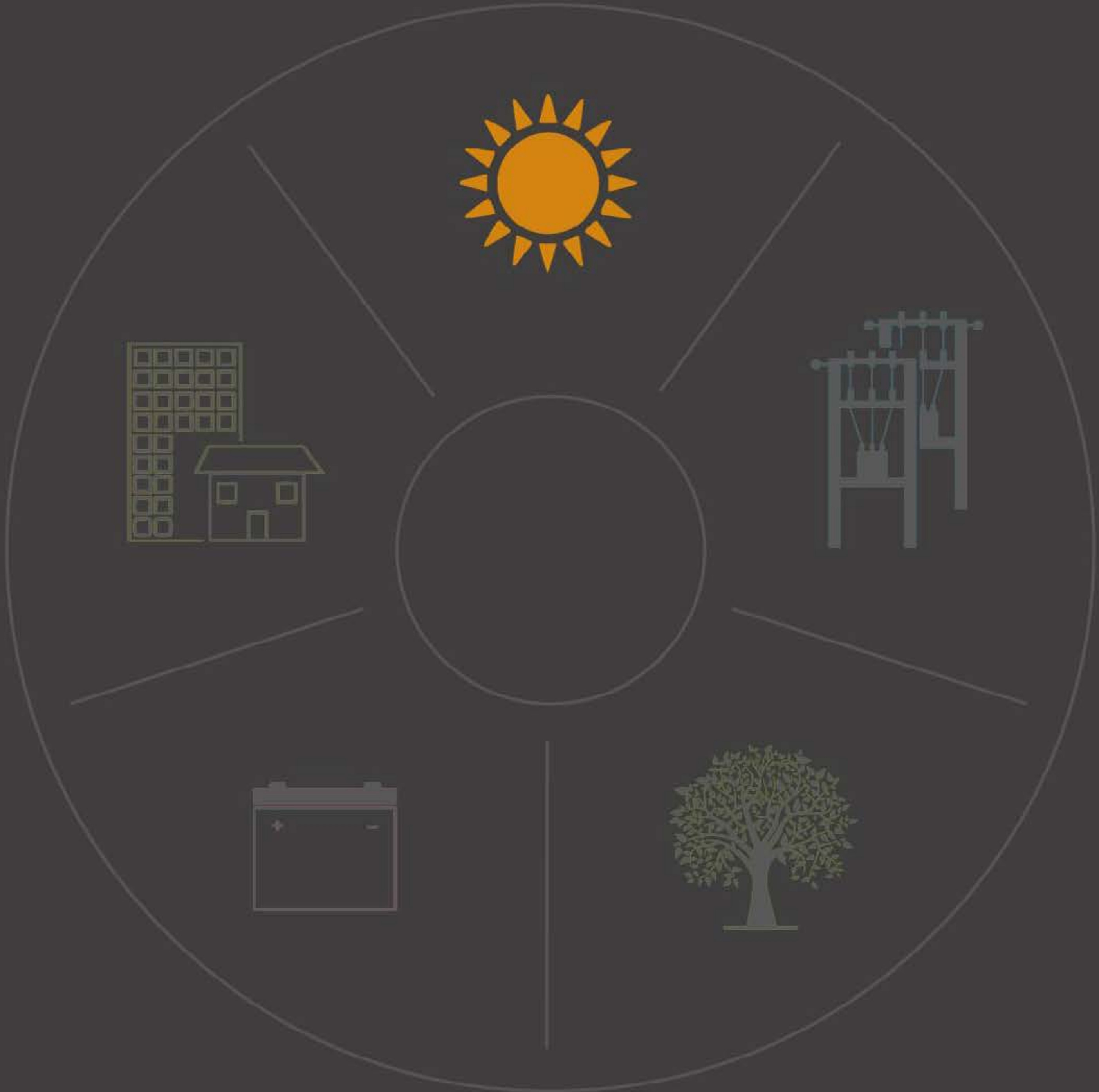
Introduction



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INTRODUCTION

The grid-connected SPV systems are the most efficient; the stand-alone off grid systels require higher battery capacity to avoid downtime

The purpose of this study is twofold. First, it is to better understand the energy situation in Auroville communities that do not have electricity grid supply (either by choice or due to external circumstances). Second, the study attempts to determine how the energy systems can be improved upon after taking technical, economic, social and environmental parameters into account.

The study has been structured in four parts.

Part 1 studies seven configurations of energy systems most commonly found in Auroville, based on technical, economic, social and environmental sustainability. It includes measurements of energy sourced, energy consumed, energy losses, reliability and availability of electricity.

Part 2 focuses on storage technologies. This Part of the research, examines whether it is worthwhile to replace the existing Flooded Lead Acid batteries that are most commonly found in Auroville, with either the Valve-Regulated Lead Acid batteries or Lithium-Ion (Li-ion) batteries by considering technical, economic, social and environmental parameters.

Part 3 of the study, focuses on a sample of five communities in the Green Belt that presently have no grid supplyof electricity, with the objective of determining how the existing Solar Photovoltaic (SPV) systems can be improved. Based on the findings in Part 1 and Part 2, as well as on site observations, different interventions have been recommended.

Finally, Part 4 provides a list of all off-grid buildings in Auroville, along with cost estimates for connecting all of them to the grid together with implementing different solutions as proposed in the previous Parts of the study.

Executive Summary

Part 1 compares seven configurations of energy systems most commonly found in Auroville, based on technical, economic, social and environmental sustainability, in order to determine the most optimum one.

The efficiencies of batteries and inverters were measured, and a simulation tool was developed to evaluate the efficiency of the overall system. The study found that the Grid-connected SPV systems are the most efficient; it was also found that the stand-alone off grid systems require a higher battery capacity to avoid downtime.
The levelised costs were estimated for each system, and it was found that the batteries comprise the highest proportion of the costs; hence it was found that a grid-connected system without battery backup is the most economical followed by a conventional grid system without SPV. The next most economical system was found to be the grid-connected SPV system with battery backup. The level of maintenance required for each system was also considered, and it was found that the costs depend specifically on the site conditions as well as the technical proficiency of the site steward.

To better understand the social impact of each energy system, eleven site stewards were surveyed on social parameters (such as impact on lifestyle, maintenance and daily operations, understanding of the system, energy security, and so on). Grid-connected SPV system with batterybackup was found to be the most desirable energy system, and Stand-alone solar system as the most constraining system.

Next, a life cycle analysis of each system configuration was studied. The embodied energy used to manufacture the system, as well as its energy footprint greenhouse gas emissions over a lifetime of 20 years was calculated. It was found that a grid-connected SPV system without battery has the lowest impact on the environment, followed by its equivalent with battery backup. A stand-alone system has the highest carbon footprint because of the high battery capacity it employs. It was also found if the SPV system is underutilized then a Hybrid (Grid and SPV) system with battery has as much an adverse environmental impact as a conventional grid system with battery backup.

Part 2 compares two battery chemistries: lead acid and lithium-ion, by analysing the two based on technical, economic, social and environmental parameters. Each technology has its own set of pros and cons based on application and use. Technically, Lithium-ion (Li-ion) batteries are superior to Flooded Lead Acid (FLA) batteries as well as the Valve Regulated Lead Acid (VRLA) batteries in every aspect, including lifetime, efficiency, discharge rate, self-discharge during idle time, depth of discharge, gas emissions and thermal runaway. Also, it was found that between VRLA and FLA battery types, VRLA is the better alternative, as they are safer to use and maintain, and also have a longer length of life.
Cost per Kilowatt-hour (kWh) delivered by each battery type over its lifetime showed that VRLA batteries are more economical than Li-ion. However, if a shallow depth of discharge is considered, then Li-ion batteries become competitive due to their higher efficiency.

A study on the embodied energy of the different battery types revealed that an annual gain of 7% of embodied energy (&12% on greenhouse gas emissions) would be realized if FLA batteries of stand alone SPV systems were replaced by their VRLA counterparts; and the gain would be 33% on the embodied energy (& 27% on greenhouse gas emissions) if FLA batteries were replaced by Li-ion.At the same time, it must be noted that recycling facilities for Li-ion batteries do not exist in India as yet, and also, the recycling process is currently more costly and complex. Hence, although Li-ion batteries have a lower environmental impact than Lead Acid batteries, recycling them is still an issue.

Based on the findings of the study, we considered different interventions at the building level as well as at the community level in Auroville. Although Li-ion batteries are better than the Lead Acid batteries, we are of the opinion that the high performance promised by Li-ion may not be required in Auroville, especially since buildings in the Greenbelt have small domestic loads that do not need a high rate of charge or discharge. Also, since the eco-system for the Li-ion batteries (such as the sales, service, recycling facilities, etc.) is not widespread in India as yet, we recommend that for now, all FLA batteries in the Greenbelt are systematically upgraded to the VRLA type, and in parallel, a pilot Li-ion battery system is installed as a centralized storage system, in order to verify its performance and efficiency. If the ease of use of Li-ion battery is confirmed, a conversion of all batteries in the Greenbelt to Li-ion will be highly profitable, from an environmental perspective.

Part 3 of the study, focuses on a sample of five communities in the Green Belt that presently have no grid supply of electricity, with the objective of determining how the existing Solar Photovoltaic (SPV) systems can be improved. Based on the findings in Part 1 and Part 2, as well as on site observations, different interventions have been recommended.

Each site was visited to document the energy system configuration and record the functioning state of the system. It was found that the most stewards do not take sufficient care of their SPV system, such as cleaning the panels or keeping them shade-free, thereby not maximising the energy that could be produced from the panels. As a result many are experiencing downtime, and do not find their current energy system to be sufficient for their loads. Also, none of the sites used a monitoring device (such as the Wattmon) to manage their loads and energy production. Installing one per site will also enable proactive energy management in the site. The telephone survey revealed that only a minority (32%) favour an on-grid installation in their site, and around half (45% of those surveyed) favour a shared system of sourcing and storage (centralized system of panels and batteries).

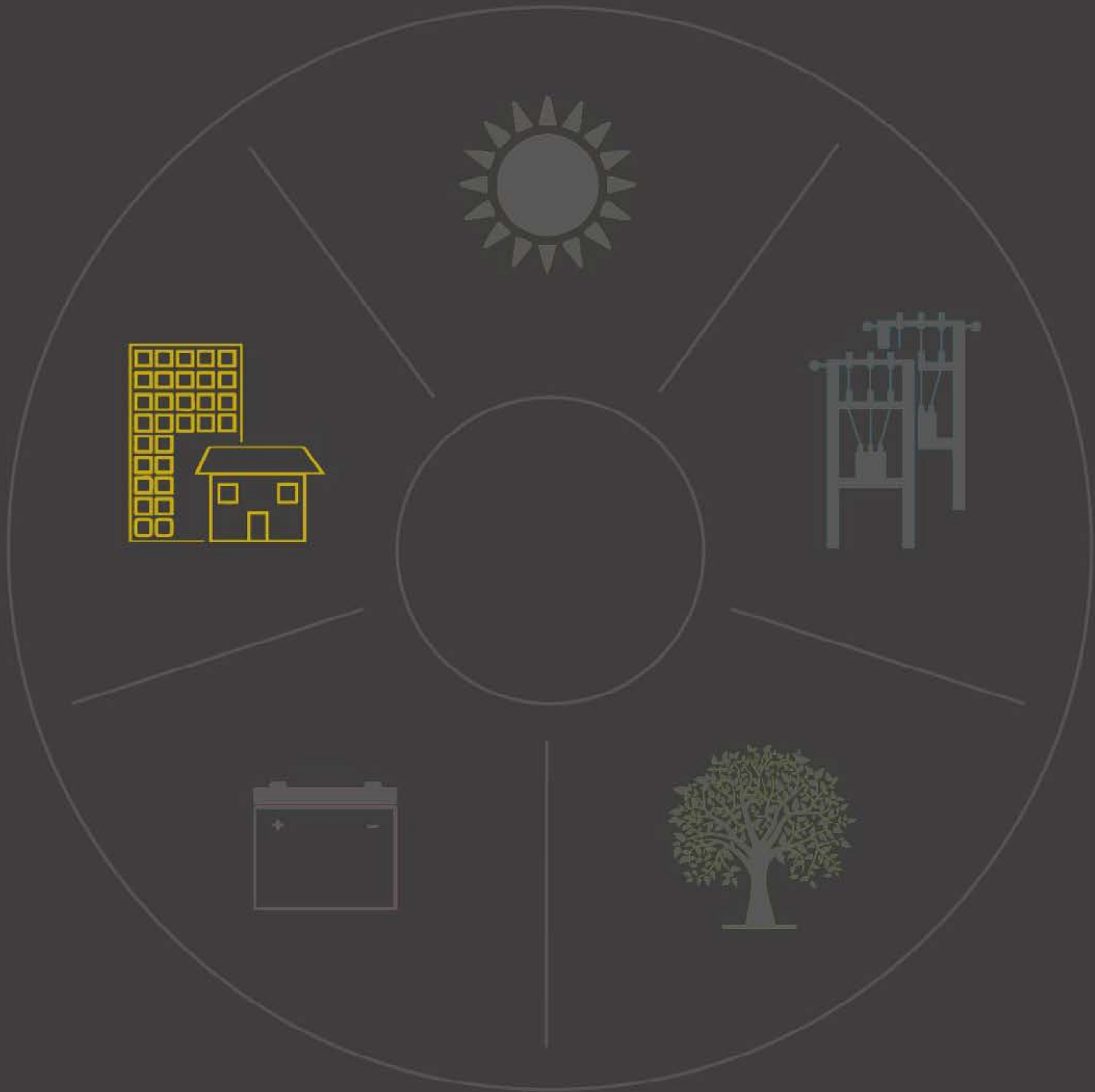
Based on the study, the following interventions have been suggested in order of priority: installing a energy monitoring device for each installation, sponsoring the maintenance of the systems, strengthening the Solar Fund and replacing Flooded Lead Acid (FLA) batteries with Valve Regulated Lead Acid batteries (VRLA). Converting the stand-alone systems to grid-interactive SPV systems would be highly beneficial from an environmental point of view, however, the relevant approvals from the Town Development Council need to be first procured. Finally, a centralized system of sourcing and storage (using Li-ion batteries) could be installed in a pilot community, to verify the performance of Li-ion technology.

Part 4 provides three lists: a list of around 130 buildings in Auroville that are off-grid, a cost estimate for connecting all these buildings to the electricity grid (approximately INR 150-200 lakhs) and a cost estimate for implementing the interventions recommended in Part 3 of the study (viz. installing a Wattmon in each site and replacing FLA with VRLA batteries estimated at INR 100-110 lakhs, a pilot installation with a centralized Li-ion battery is estimated at INR 30-40 lakhs).

The following chapters delve into each of the above in more detail.

CHAPTER 2

Cost-benefit analysis of different configurations of energy systems



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COST-BENEFIT ANALYSIS OF DIFFERENT CONFIGURATIONS OF ENERGY SYSTEMS

Context

In this part of the study we compare typical configurations of energy systems installed in Auroville, as given below.

The scope of this study is to draw conclusions on the optimal system configuration based on the following parameters:

1. Technical sustainability
2. Economical sustainability
3. Social sustainability
4. Environmental sustainability

This study will include measurements of energy sourced, energy consumed, energy losses, reliability and availability of electricity.

Type	Energy system configuration	Site	Steward
Type A	Grid supply with a grid fed backup inverter and batteries	Site 1	Vikram
		Site 2	Segar
Type B	Grid supply with a solar energy-fed backup inverter and batteries	Site 1	Bindu
		Site 2	Coriolan
Type C	Stand-alone solar photovoltaic (SPV) with an inverter and batteries with no grid backup	Site 1	Vimal
		Site 2	Toine
Type D	Stand-alone solar photovoltaic (SPV) with an inverter and batteries with grid backup	Site 1	Auroville Consulting
		Site 2	Akash
Type E	Grid-connected solar photovoltaic (SPV) without battery backup	Site 1	Toine
Type F	Grid-connected solar photovoltaic (SPV) with battery backup	Site 1	Foundation office
Type G	Grid connected solar photovoltaic (SPV) with battery backup and diesel generator	Site 1	Afsanah Guesthouse

Table 2.1

SPV configuration	No. of manual controls in a typical system	Major components	Total
Type A	0	Inverter and batteries	2
Type B	0	SPV Panels, solar charge controller, inverter and batteries	4
Type C	0	SPV Panels, solar charge controller, inverter, batteries, SPV energy monitoring device (Wattmon) and bi-directional current sensors	6
Type D	1 (Manual switch from primary solar energy to grid backup energy)	SPV Panels, solar charge controller, inverter, batteries, SPV energy monitoring device (Wattmon), bi-directional current sensors, circuit breakers and surge controllers	8
Type E	1 (Manual switch over from export of solar energy to import of grid energy)	SPV Panels, inverter, SPV energy export meter , circuit breakers, surge controllers	5
Type F	0	SPV Panels, inverter, SPV energy export meter, SPV energy monitoring device, circuit breakers, surge controllers and lightning protection	7
Type G	1 (Switch to turn on the diesel generator)	SPV Panels, inverter, batteries, SPV energy export meter, SPV energy monitoring device, circuit breakers, surge controllers, lightning protection and diesel generator	9

Table 2.2

Technical sustainability

This section analyses the selected systems based on technical parameters, viz. complexity of the system, individual efficiencies of components and overall efficiency (as an indicator of the performance of the system).To get a clearer picture of the configuration of each system, line diagrams of each system are presented in Annex 1.

Complexity of the system

Complexity refers to the number of components connected in a system. Components include SPV panels, inverter, batteries, solar charge controllers, SPV energy monitoring devices, circuit breakers, lightning protection, surge controllers etc. are vital components of a SPV system, but also tend to increase the losses in transmission and individual energy losses. More complex the system (larger the number of system components), greater would be the losses in energy, and lower the efficiency of the system as a whole. Successful long term operation and maintenance of the system demands knowledge and technical know-how of these individual components.

The overall efficiency of each system will be impacted by the individual efficiency of the components. The more components causing energy losses to the system, the less efficient the system will be. The two main factors that contribute to the overall efficiency of a SPV system are inverter efficiency and battery efficiency. Another factor is the panel efficiency but it is not directly measurable.

For systems importing energy from the grid, losses in transmission from the plant to the facility have been taken into account. To get experimental values of efficiencies different monitoring systems have been used, due to the fact that some sides had already a monitoring system installed or it was not deemed feasible to install an additional one. The equipment used in the study was the Wattmon Solar Monitoring System, the Voltcraft Energy Logger 4000, Delta Solivia Monitoring System, PV Output Monitoring System, as well as already installed E-Meters. The efficiency of the components was calculated using the following formulas.

Efficiency of the inverter when converting into Alternating Current (AC):

$$Eff_{inverter\ AC} = \frac{\text{Units on inverter AC output}}{\text{Units on inverter DC input}}$$

Units AC output =
(Units DC input x $Eff_{inverter\ AC}$)-Inverter static consumption

Efficiency of the inverter when converting into Direct Current (DC):

$$Eff_{inverter\ DC} = \frac{\text{Units on inverter DC output}}{\text{Units on inverter AC input}}$$

Units DC output =
(Units AC input x $Eff_{inverter\ AC}$)-Inverter static consumption

The energy loss of the conversion process consists of a dynamic and a static component. The dynamic component depends of the amount of energy, which is converted. This efficiency is called "pure efficiency". The static component is the energy which is needed to keep the inverter running and can therefore be seen as a parasitic load. With small loads the static component will reduce the efficiency significantly. The bigger the load, the smaller the influence of the static component and efficiency will improve. It is therefore important to notice the inverter yield when stating the efficiency.

Efficiency of battery charging and battery discharging:
A battery's efficiency is determined through two coefficients, the charge coefficient and the discharge coefficient. These two coefficients

depend on the current state of charge of the battery. The presented formulae were applied over the long-time usage data of the battery of each system, the coefficients determined are therefore a representation of average working conditions. For calculating the efficiency of the battery it is better to compare the two coefficients, because this method is not bound to static charge and discharge intervals.

Charge Coefficient:

$$Eff_{charge} = \frac{\text{Delta state of charge}}{\text{Units charged}}$$

Discharge Coefficient:

$$Eff_{discharge} = \frac{\text{Delta state of charge}}{\text{Units discharged}}$$

Battery complete efficiency:

If we assume the battery gets discharged and charged back to the same level, then we can combine both equations to get the equation for the battery efficiency.

$$\text{Units charged} \times Eff_{charge} = \text{Units discharged} \times Eff_{discharge}$$

$$Eff_{battery} = \frac{\text{Units discharge}}{\text{Units charged}} = \frac{Eff_{charge}}{Eff_{discharge}}$$

However when the state of charge differs after a discharge-charge-period, which is the usual case under working conditions, only the relation of the coefficients will be used to determine the efficiency. The following efficiencies were determined for components of the various systems using the different monitoring systems.

These onsite experiments have shown that the efficiency of a battery varies from 70% to 80%, Inverter's efficiency while converting DC to AC between 77.5 and 91.2%; while converting AC to DC between 72.7 to 93.3%. It shows that the type, brand or quality of the battery or inverter leads to wide variations of the efficiency. Also, manufacturer specifications tend to indicate a higher efficiency than what was found experimentally.

SPV configuration	Site	Battery efficiency	Inverter efficiency(DC to AC conversion pure)	Inverter efficiency (AC to DC conversion pure)	Monitoring System
Type A	1	42.0%	83.6%	72.7%	Wattmon, Voltcraft
	2	72.9%	84.6%	67.9%	Wattmon, Voltcraft
Type B	1	75.3%	No Data	No Data	Wattmon, Voltcraft
	2	71.8%	No Data	No Data	Wattmon
Type C	1	70.3%	77.5%	N.A.	Wattmon, Voltcraft
	2	71.1%	78.5%	N.A.	Wattmon, E-Meter
Type D	1	79.5%	91.2%	93.3%	Wattmon, Voltcraft
	2	75.9%	No Data	No Data	Wattmon
Type E	1	N.A.	No Data	N.A.	E-Meter
Type F	1	No Data	No Data	N.A.	Delta Solivia
Type G	1	No Data	No Data	N.A.	PV Output

Table 2.3

Overall efficiency of a system:

To calculate the efficiency of the whole system one has to analyse the flow of power between the components in each type of system. Although one cannot determine the efficiency of the whole system with just the efficiency of its parts, it could be said as a general rule, that components with higher efficiency will result in a system of a higher total efficiency.

In order to determine the path taken by the energy over running time of a system, a simulation tool has been designed. Assumptions concerning the load profile used for simulation purpose, the set of components chosen and the static data (solar irradiation, individual efficiencies, etc) are detailed in the annex. The simulation tool determines the flow of energy every minute and calculates system efficiency depending of the different power flows. There are two efficiencies calculated: the efficiency without inverter idle power loss and the efficiency with inverter idle power loss. The energy lost in the inverter can be considered as a load required for running the system, the bigger the actual load consumption compared to the idle inverter loss, the lesser its impact on the overall efficiency. “Downtime” represents how many minutes per week when power is not be available. Ideally the system should be designed to withstand extended periods of low solar power and grid power cuts without leading to downtime for the steward; downtime could indicate that the simulated system is not scaled correctly.

Energy passes through different components as it moves from the point of generation to to the point of consumption. The components that it passes through vary from system type to system type, and each component has its own energy needs to operate, and hence its own efficiency level. For instance, if energy is travelling from the solar panels directly to the load it has a better efficiency than if energy is stored in a battery and discharged later due to battery inefficiency. By multiplying the efficiencies of the individual components in each system type, and then dividing it by the amount of total power travelling through the system we get our average efficiency of the system. For example, efficiency of a Type C system:

$$\frac{Solar_{load} \times Eff_{inverter\ AC} + Solar_{battery} \times Eff_{inverter\ AC} \times Eff_{battery}}{Solar_{load} + Solar_{battery}}$$

If we take inverter loss into account,efficiency of a Type C system:

$$\frac{Solar_{load} \times Eff_{inverter\ AC} + Solar_{battery} \times Eff_{inverter\ AC} \times Eff_{battery}}{Solar_{load} + Solar_{battery} + Inverter_{loss}}$$

Efficiency figures presented here are just representatives of the overall effectiveness of the system type to convert energy, for two load profiles, viz. a typical domestic load profile, and a typical office load profile.

The team was faced with the following challenges while collecting and analysing data from the various system types

- Lack of proper measuring equipment
- Varying monitoring equipment and sources of data
- Inaccuracies in the monitoring equipment
- Inability to collect data from certain sites due to ongoing construction
- Hugh variation in the system setups and state of components.

Domestic load profile	Type A	Type B	Type C	Type D	Type E	Type F	Type G
Energy input (kWh)							
Grid energy used	13.27	5.08	-	13.21	8.60	9.08	8.60
Solar energy generated	-	11.39	11.39	11.39	11.39	11.39	11.39
Solar energy used	-	7.45	7.45	7.45	7.45	7.45	7.45
Energy dispersion (kWh)							
Solar to load	-	4.46	4.46	4.46	4.46	4.46	4.46
Solar to battery	-	3.24	6.11	0.42	-	0.06	-
Grid to load	11.52	5.08	-	5.88	8.60	8.60	8.60
Grid to battery	1.75	-	-	7.33	-	0.48	-
Diesel to load	-	-	-	-	-	-	0.39
Energy output (kWh)							
Solar to Grid (export)	-	-	-	-	5.68	5.63	5.68
System efficiencies (%)							
Total efficiency	75	69	57	46	84	82	83
Total efficiency (inverter loss)	58	52	41	38	69	69	68
System performance (min)							
Downtime per week	0	0	791[3]	0	284	0	0
Diesel generator running time	-	-	-	-	-	-	0

Table 2.4

[3] Important downtime here indicates that the battery is oversized, or that such high loads are not applicable in the context of a stand-alone system.

Office load profile	Type A	Type B	Type C	Type D	Type E	Type F	Type G
Energy input (kWh)							
Grid energy used	20.95	2.29	-	2.03	5.43	5.22	5.16
Solar energy generated	-	23.06	23.06	23.06	23.06	23.06	23.06
Solar energy used	-	15.83	15.83	15.83	15.83	15.83	15.83
Energy dispersion (kWh)							
Solar to load	-	15.27	15.27	15.27	15.27	15.27	15.27
Solar to battery	-	2.28	3.94	1.70	-	0.17	-
Grid to load	19.21	2.29	-	3.10	5.16	5.16	5.16
Grid to battery	1.74	-	-	0.49	-	0.06	-
Diesel to load	-	-	-	-	-	-	0.31
Energy output (kWh)							
Solar to Grid (export)	-	-	-	-	5.82	5.67	5.82
System efficiencies (%)							
Total efficiency	79	88	87	89	91	91	91
Total efficiency (inverter loss)	67	74	73	75	80	81	79
System performance (min)							
Downtime per week	0	0	0	0	154	0	0
Diesel generator running time	-	-	-	-	-	-	0

Table 2.5

Conclusion:

The different systems have been ranked based on efficiency and downtime, for domestic and office load profiles. Types E, F and G rank better that the other system types in both load profiles. Out of these 3 systems F is especially preferable because it is able to compensate for power cuts due to its back up battery; this is also achieved in Type G via a diesel generator. Besides the relatively high efficiency of energy conversion, Types E, F and G can also feed excess energy back to the grid unlike Types B, C and D in which excess energy goes waste. Type A provides a stable system for energy supply, but the user has to weigh the value of uninterrupted power against the potential energy loss resulting from the inverter and battery.

In Type C system one is strongly reliant on the solar power provided. Because there is no grid backup a bigger scaled battery is necessary to provide uninterrupted power, or the system constrains the user to use lower loads. The downtime calculated for the domestic profile shows clearly that an under scaled battery bank leads to high downtime. Also, the relatively high use of the battery is negative for the overall efficiency of the system and makes it unattractive.

System type D is particular inefficient since the grid is used to charge the batteries, which is a process with high loss because of the many stations of transmission along the way. The main difference to the Type F system is that the grid is turned on, only when the battery voltage drops below a certain level. The constant charging and discharging of the battery is inefficient in terms of energy conversion and also drains the lifetime of the battery. In conclusion, Type F is the most appropriate solution in terms of effectiveness and efficiency.

System type / Ranking	Type A	Type B	Type C	Type D	Type E	Type F	Type G
Efficiency (domestic)	4	5	6	7	1	3	2
Downtime (domestic)	1	1	3	1	2	1	1
Efficiency (office)	5	3	4	2	1	1	1
Downtime (office)	1	1	1	1	2	1	1
Final ranking	4	3	5	4	2	2	1

Table 2.6

Economical parameters

The following section aims to quantify the economic value of the different system configurations. Original bills of the systems have not always been maintained by the site steward or by the installer. As a result, we have taken average market price, and retro-priced each device to the year of installation, in order to estimate the cost of the initial investment, depreciation, cost of maintenance, resale value and cost of replacement. The following table lists the assumptions and values for these calculations:

Device	Item	Value	Source
SPV Panel	Avg. price per watt of a panel	Rs. 50	Source: Part 1/Sunlit Future
	Price per Watt in 2008	Rs. 80	Source: Sunlit Future
	Average resale value	Rs. 100	Source: EcoService
	Depreciation per year	80%	Prabhasari Accounting
Inverter	Price per kVA	Rs. 6,786	Calculated field
	Price per kVA in 2010	Rs. 6,786	Source: Sunlit Future
	Average resale value	Rs. 2750	Source: EcoService
	Depreciation per year	25%	Prabhasari Accounting
Battery	Cost of maintenance per month	Rs. 50	Source: Sunlit Future/Solar Service
	Cost for FLA battery, per Wh	Rs. 8.5	Source: Solar Service
	Cost of FLA per Wh in 2011	Rs. 11.05	Source: Sunlit Future
	Average resale value	Rs. 1,500	Source: EcoService
	Cost per Wh of VRLA	Rs. 10	Source: Sunlit Future
	Cost per Wh of Li-ion	Rs. 49	Source: Sunlit Future
	Depreciation per year	25%	Prabhasari Accounting
Charge controller	Average price	Rs. 6,000	Source: Sunlit Future
	Price in 2010	Rs. 6,000	Source: Sunlit Future
	Depreciation per year	25%	Prabhasari Accounting
Diesel generator	Average price per kVA	Rs. 6000-9000	Source: EcoService
		25%	Prabhasari Accounting

Table 2.7

Based on the above, the costs of each system in the sample sites are presented in the graph below.

The sites that were chosen varied considerably in terms of size and purpose. We calculated the levelised costs for standardised systems of each Type, with the assumption that all the systems use FLA batteries sized accordingly to the type of system , and that each component has to be replaced as many times as needed to match the lifetime of a SPV module (20 years).

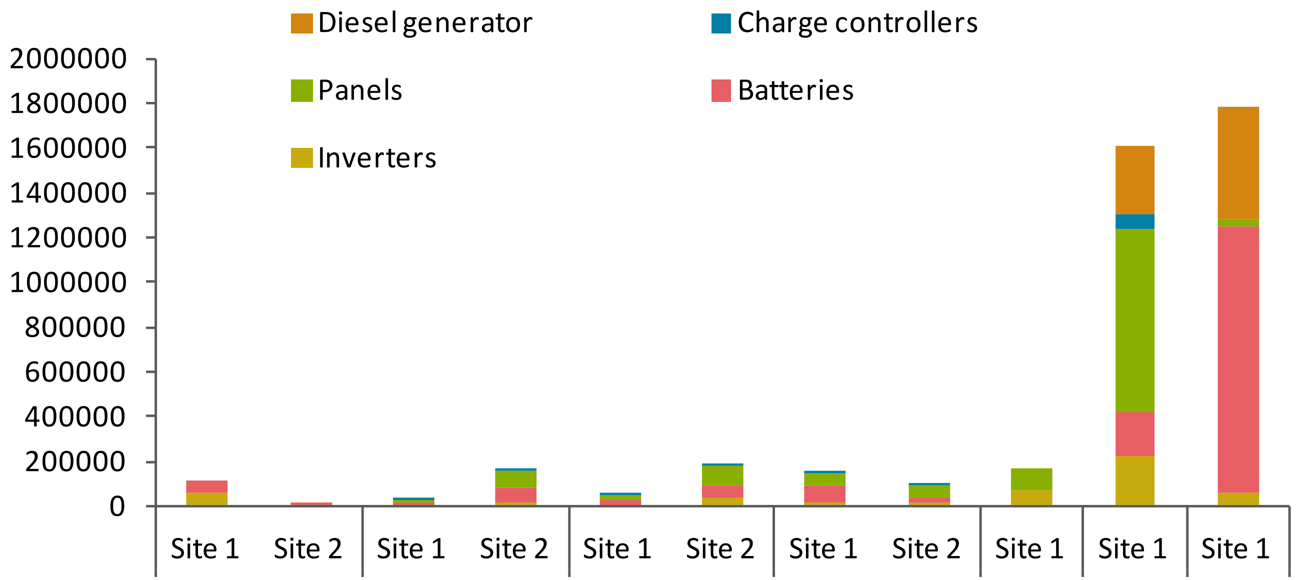


Figure 2.1

The levelised costs are presented in the graph below.

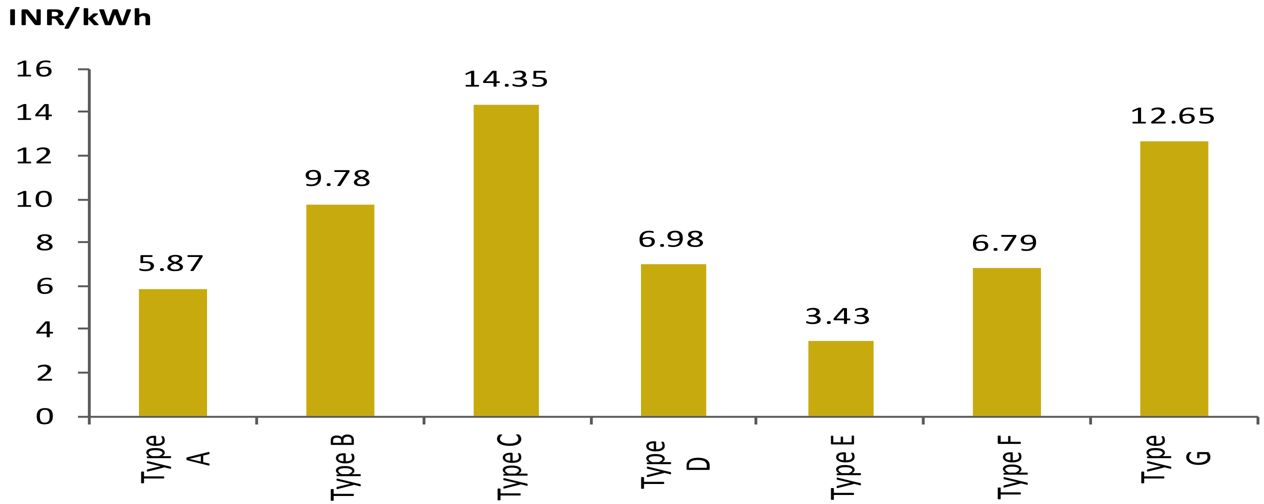


Figure 2.2: Levelised costs of different system types

Those costs per kWh show that due to the initial setup costs, mainly due to the high battery capacity required, Type C system is the most expensive. Type A is the second cheapest option, as only batteries have to be purchased and due to the subsidised price of grid electricity in Tamil Nadu. Type E is the most economical option, mainly due to the absence of batteries. Batteries are clearly the main factor for high cost per kWh, as they are costly and have to be replaced often. Note that for grid-connected systems, we have considered net metering and not feed in tariffs.

Initial investment and depreciation

The following graph shows the approximate cost of initial investment and current book value of each System Type. Costs are indicated relative to the number of people in the facility (number of residents in case of a household, number of staff in the case of a commercial facility, etc)

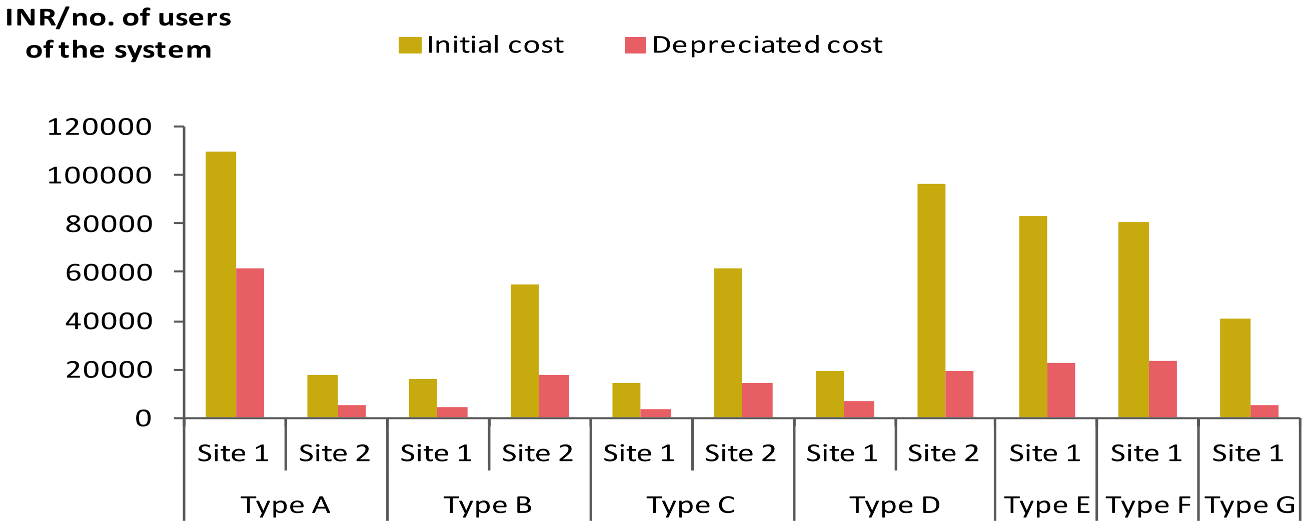


Figure 2.3

Maintenance costs:

Over the years, as the equipment approaches its lifetime, the efficiency and reliability on the equipment will fall, increasing the cost of maintenance. More the number of components connected in a SPV system configuration, higher the maintenance costs. The maintenance costs related to SPV panels, are primarily the costs for

the water required to clean the SPV panels. The water tariffs, currently at Auroville are priced at Rs. 18 per cubic meter of water consumption (AWS, 2014). Diesel generator is the most expensive component to maintain, followed by batteries and inverter maintenance.

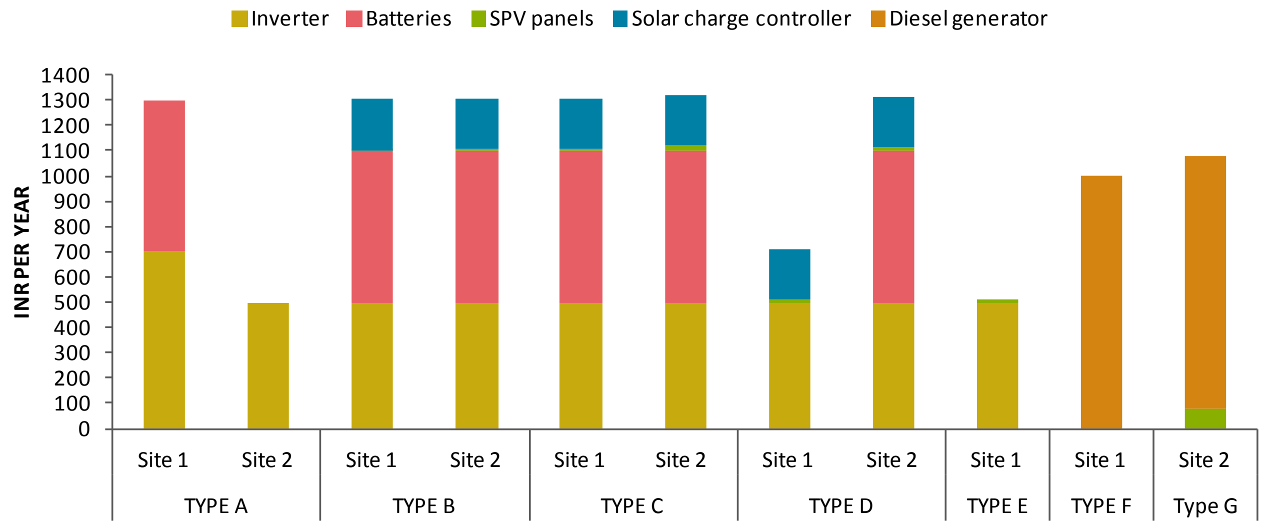


Figure 2.4: Annual cost of maintenance for each component

Replacement cost

If all system components were to be replaced in one go at current market prices, then the total investment cost will be as shown in the graph below. Scrapping or reselling the components reduces replacement costs, but only marginally. Resale prices of components depend on their age and working condition. If the component is still working it can be reused, else the copper and wire in the inverters and charge controllers can be reclaimed and wolf back to the manufacturers. Panels cannot be recycled, but the glass is valuable; average resale value is Rs.100 per panel.

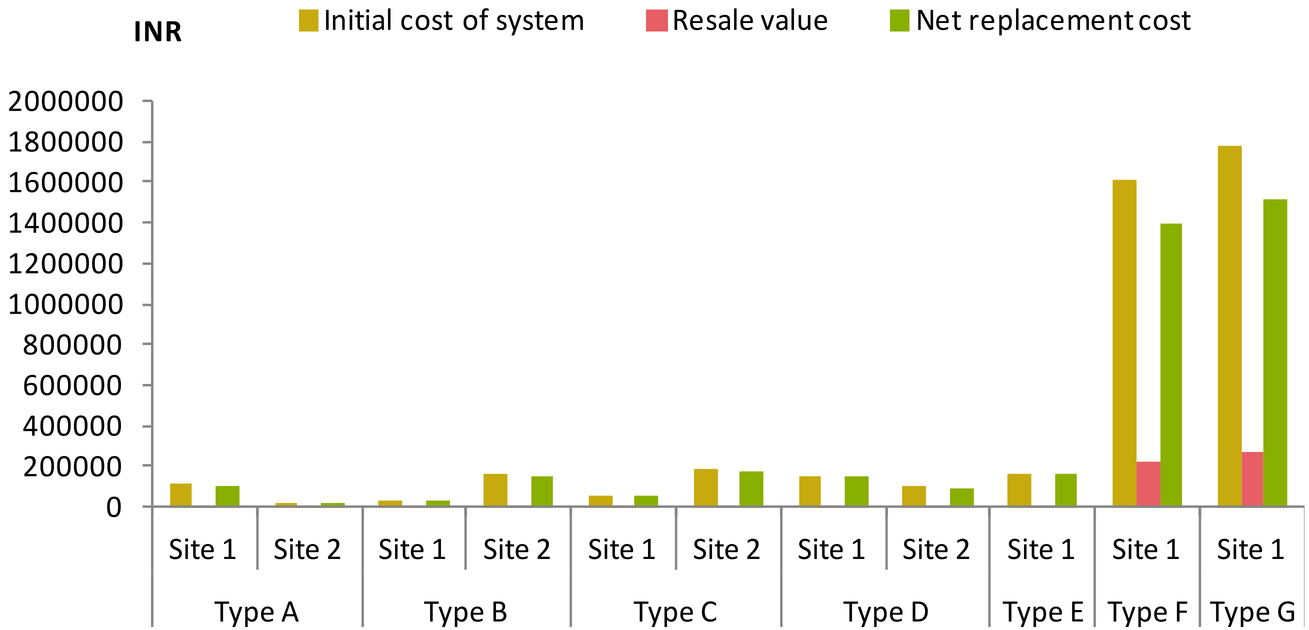


Figure 2.5

Conclusion

Levelised cost (INR/kWh) is the main factor that can describe the economic parameters of a typical configuration. This depends mainly on the battery capacity in the system, which is itself dependant on the level of comfort the user wishes to have. The different system types have been ranked based on the economic parameters used on this study. Type E is the most economic system configuration followed by Type A and Type F. Type C was found to be the most costly system configuration.

Table 2.8

System type / Ranking	Type A	Type B	Type C	Type D	Type E	Type F	Type G
Levelised cost	2	5	7	4	1	3	6

Social parameters

This section compares the different systems from social perspective based on the following parameters: impact on lifestyle, acceptability, level of comfort, energy security, safety and economics. A telephone survey and face to face survey was conducted of the 11 sites selected for the study. Out of the 11 installations, 6 are residences, 2 are guest houses and 3 are offices or commercial units. Households are mostly small in size with 1-4 residents. Two buildings are not equipped with energy monitoring systems such as the Wattmon or other energy monitoring devices. All of this contributed to very disparate profiles of users which have impacted the results of the study. Scores were assigned to each attribute; higher the score, better the social impact of the system on the site steward.

Impact on lifestyle

Impact on lifestyle refers to the level of knowledge required to use the system, the changes in behaviour and lifestyle after implementation of the system, the eventual loss of usable space and territorial adjustment, ability to scale up the system, and the technical assistance needed by the steward to operate and maintain the system.

Types A and F were found to be easiest to use. All the systems seem to be working autonomously, except type C; wherein the system was being turned off in case of lightening. In Type D, both sites are equipped with Wattmon which has been automated to reduce user intervention. Types B and E required very little from the site steward in terms of operation and maintenance. The need of higher consciousness of energy consumption when batteries were charged by solar, stewards of Types F & G, were especially careful during the monsoon. The availability of sunlight, determined the planning of daily chores for Type B-2, C-1 and E. Implementation of Type A did not impact the lifestyle or behaviour of the stewards.

Stewards of Type C were very conscious of the amount of energy remaining in the battery, and entailed the highest impact on the lifestyle of the steward, and resulted in higher awareness of energy consumption (C-1&2). In case of type D-2, the fact that Wattmon provides an overview of the state of the system, helped the user adapt to the system. It should be noted that in the case of Type B-2 and G-1, there has been an increase of electricity consumption since the system has grid back up.

The loss of usable space depended mainly on the previous system configuration, e.g. If a room had been built especially for the system (in case of Type C-1) or if the system had to be increased in size (in case of Type G-1). Only Type A-1 and D-1 lost usable space. Concerning territorial changes, only Type D-1 required pruning of trees, while Type G-1 a levelling of land. The technical assistance needed to take care of the system depended more on the profile of users: people taking care of the system themselves require support only when a problem occurs.

The following graphs present the findings of the survey on these points, by site, and as an average by System Type.

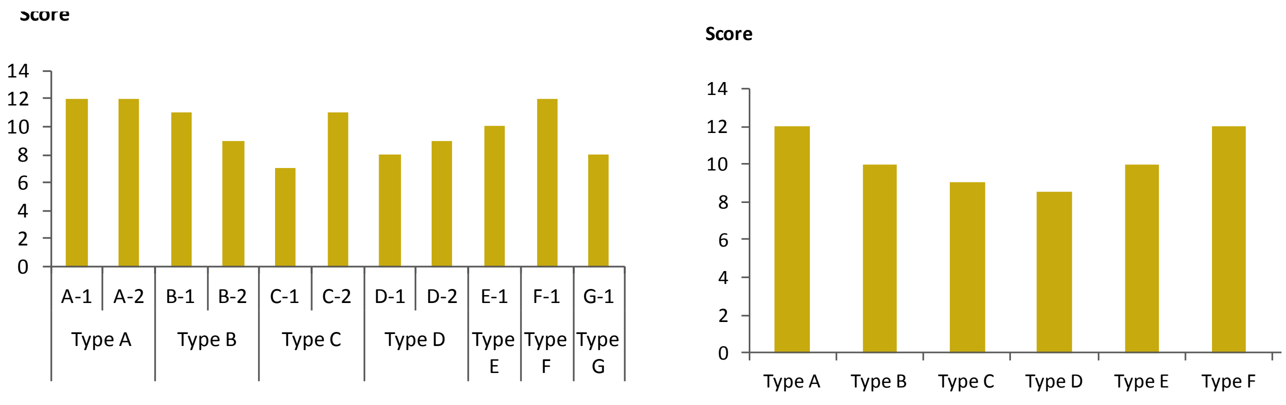


Figure 2.6: Lifestyle scores per site (left) and averaged (right)

Acceptability

Acceptability refers to the ease of understanding of the system, the level of satisfaction, and whether it could be recommended at a community wide scale based on social parameters. Difficulty to accept an energy system, comes from the difficulty to understand the system configuration viz. Type B-2, C-1, D1&2. Acceptability is highest in case of Type G. It is actually the only site where there are 3 sources of energy: solar, grid and diesel generator. Note that Acceptability depends on the profile of user: the user of Type G understands well how the system works and is satisfied with using these 3 sources of energy, which allows high reliability of energy. Acceptability is less in case of Type D; the users do not consider this system as understandable by a layman and they do not completely understand how their system works

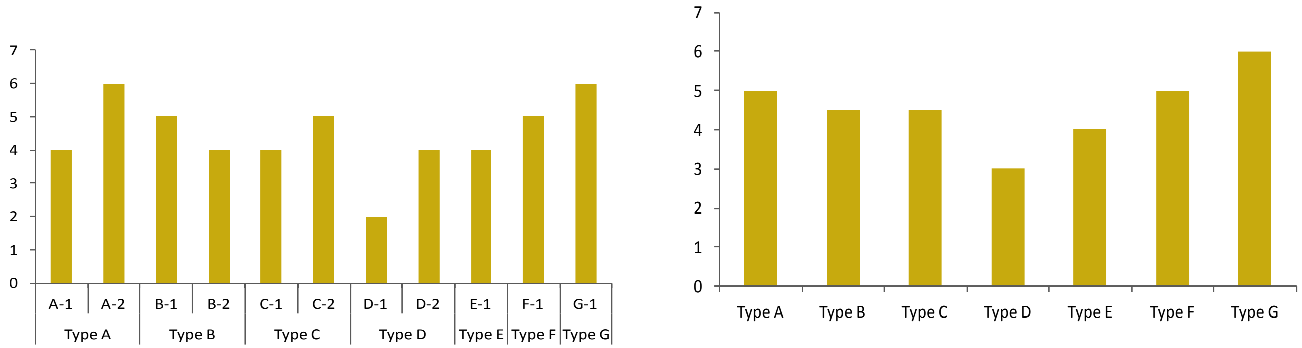


Figure 2.7: Acceptability scores per site (left) and averaged (right)

Level of comfort

Level of comfort is defined by the consistency of energy provided by the system, the level of risks encountered and the frequency of manual interventions needed. The system providing less comfort is Type C. Both sites reported not to have uninterrupted supply during the monsoon or on cloudy days. Type A-1 and C-2 have reported a risk of acid spill when they open the battery; it is induced by the fact that they maintain the batteries themselves. Surveying the frequency of manual interventions highlights the fact that users do not maintain the same component with the same frequency; in case of type C-2 the panels are cleaned once a month, in case of D-1 once a week. The type of battery (FLA or VRLA, which is maintenance-free) also impacts the frequency of manual interventions and is not linked to the type of system.

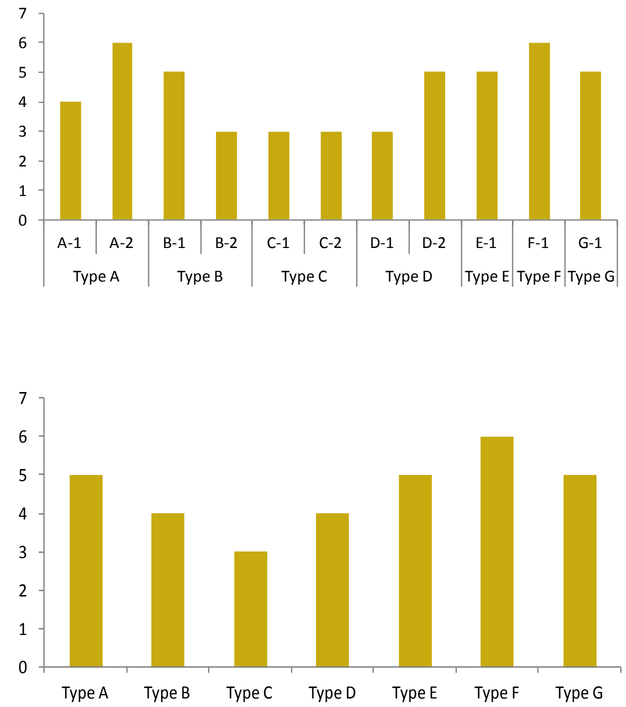


Figure 2.8

Energy security

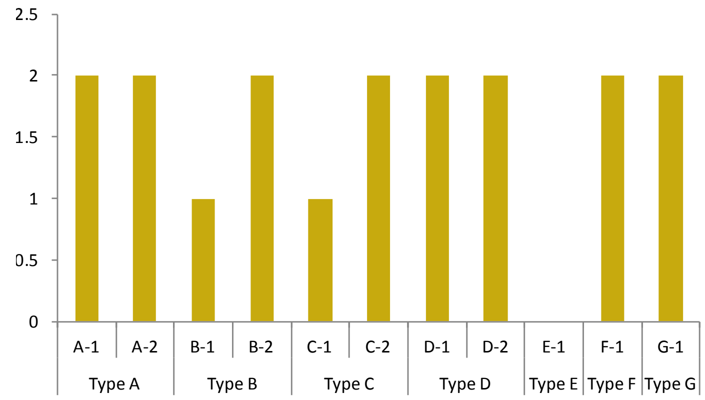
Energy security refers to the capability of a system to provide consistent supply during power cuts. The biggest constraint is in case of Type E: the availability of energy is completely dependent on the availability of grid, as it is a grid-connected system without battery back up. In case of type B-1, the system cannot provide energy for the refrigerator; in case of type C-1 it is not possible during monsoon or on cloudy days.

Safety

Safety refers to whether the system is equipped with lightning protection, safety fuses, and anti-fire system. Many users were not aware of the safety devices in their system. 5 sites out of 9 mentioned that they do not have any anti-fire systems, and 3 among them are not equipped with lighting protection. However this question is not related to the configuration of the system.

Economics

Economics refer to the ease with which the system was funded, as well as the monthly maintenance expense. The diversity of sites selected for the study (individual households, office, unit, guesthouse, etc) results in a wide range of answers. Type B-2, C-1 and G reported high difficulties to fund their initial investment. Little difficulties were encountered by system A-1 and B-1. Answers to this question depended on availability of a solar fund or



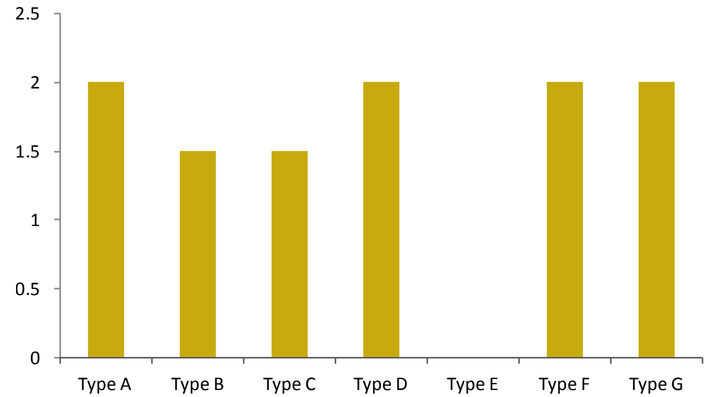


Figure 2.9: Energy security scores per site (above) and averaged (below)

help from institutions for funding. Hence, it does not seem to depend on the type of system configuration. For all systems, monthly costs of maintenance are low.

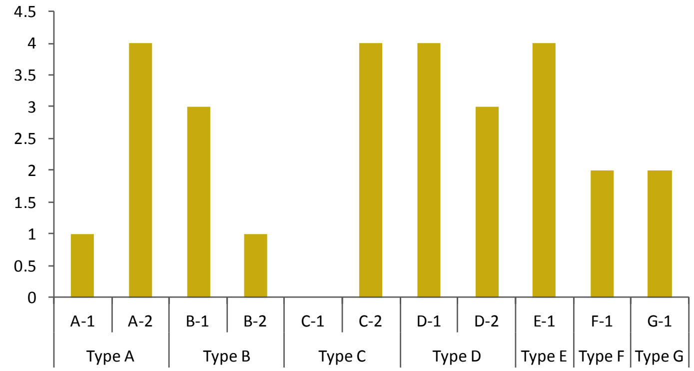
Conclusion

Each system configuration was ranked based on the above mentioned social parameters discussed above, as shown in the table below. Broad conclusions are as follows

- Grid-connected systems (Type E, F & G) seem to be the best option while considering all the social criteria, among which, grid-connected solar system with battery back-up seems to be the best combination to fulfil all needs.

- All the answers impacting the scores depend on the profile of user (layman, expert in solar systems, etc) and/or type of facility (unit, simple household, guesthouse, etc). Priorities are not the same for everybody (some will not be satisfied having a system with a battery because it is not eco-friendly, some will be very happy having reliable electricity supply due to grid and diesel generator in addition to solar).

- Some specifics of each installation (type of battery, user maintaining the system himself, etc) impacted the answers without being linked to the configuration of the system.



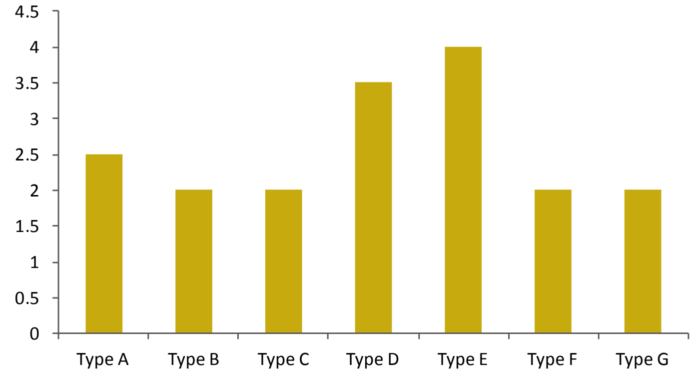


Figure 2.10: Economics scores per site (above) and averaged (below)

- Such criteria have to be taken into account because different profiles of users do not react the same way to the same system. As a result, implementing one type at a large scale should be done carefully. In order to have a representative sample of profiles of users, the study needs to be conducted at larger scale before drawing conclusions for the community as a whole.

System type / Ranking	Type A	Type B	Type C	Type D	Type E	Type F	Type G
Lifestyle	1	2	3	4	2	1	5
Acceptability	5	4	3	5	3	2	1
Level of comfort	5	3	4	3	5	1	2
Energy security	1	2	2	1	3	1	1
Economics	3	4	4	2	1	4	4
Final ranking	4	4	5	4	3	1	2

Table 2.6: Ranking of systems on social parameters

Environmental parameters

In order to rate the impact of each configuration on the environment, this section calculates the Energy footprint and Greenhouse gas emission through a Life-Cycle Assessment, and estimates the land and water footprint of each installation. Methodology for calculation is provided in Annex.

Energy footprint and greenhouse gas emissions

While there are no global warming emissions or consumption of energy associated with generating electricity from solar energy, there are emissions and embodied energy associated with other stages of the solar lifecycle, including manufacturing, materials transportation, installation, maintenance, and decommissioning and dismantlement. The main components of solar PV panels are made from crystalline silicon. Manufacturing these components is an energy-intensive process. The exact carbon footprint of any particular solar panel depends on many factors, including the source of the materials, the distance they have to be transported and the energy source used by the manufacturing plants. For example, China, a leading producer of solar PV panels, is heavily reliant on coal-fired power stations, which contributes to the carbon footprint of solar panels made in China (EDF Energy, 2011). All the manufacturing, assembly, transportation, installation and recycling of PV modules and Balance of System (BOS: inverters, charge regulators, batteries, supporting structures) consume energy, which is referred to as Embodied Energy (Garcia-Valverde, 2009).

In order to determine the global energy footprint and the greenhouse gas emissions for each system, we have conducted a Life-Cycle Assessment (LCA) using the following assumptions. Changing any of the following assumptions will change the final conclusions of this study.

- Embodied energy varies considerably according to the components used and the place of manufacture. Unfortunately, data for India does not seem to be available. Consequently, much of the data used in this study are based on studies undertaken in other countries. As we are focusing on multi-crystalline PV systems manufactured in Asia, we chose mainly the data proposed by Kaldellis (Kaldellis, 2010) and De Wild-Scholten (Wild-Scholten, 2013) for the calculations presented in this study.

- A life time of 20 years is assumed for the PV facility. Components with shorter period of service are assumed to be replaced as many times as needed during the time period considered.

- The efficiency of conversion into electrical energy, considering the energetic mix used in Tamil Nadu, is 32.1% (Central Electricity Authority, 2007) and the emissions (with adjusted import and export from other states) are of 0.95kgCO2e/kWh (cBalance Solutions Pvt Ltd, 2010). Adding up the losses in transmission of 18.5% in Tamil Nadu, 3.82kWh of primary energy are needed to manufacture 1kWh electrical energy (International Energy Agency, 2011).

- As far as solar is concerned, efficiency of a panel is already captured by the figure of annual production. Due to the very small transmission distance (from place of productions the place of consumption which is in the same building), losses in transmission have been assumed to be negligible in comparison to the losses in the inverter and the batteries.

- Assessing the ratio between recycled and virgin materials being extremely difficult, all components are assumed to be manufactured from virgin materials; except for the batteries. As they have to be replaced several times during the lifetime of the system, it is assumed that the first battery comes from virgin materials, and the following ones from recycled materials.

- In stand-alone PV systems, 100% of the energy is from solar. In systems using different sources of energy (i.e. solar, grid, diesel generators), impact on environment of the different sources have been calculated relative to the actual production from these sources. This allows determining Utilization factors of each source, I.e. Solar Utilization Factor (SUF), Grid Utilization Factor (GUF) and Diesel Utilization Factor (DUF).

- Life cycle assessment (LCA) usually takes into account energy needed for decommissioning and recycling of the whole system, which makes it a study from cradle to cradle. We have conspired recycling of batteries and silicon of PV modules are taken into account, as well transportation costs (from the manufacturing plant to Auroville and from Auroville to the recycling facility). Except for copper and aluminium, the components of BOS do not seem to be recycled yet.

- Batteries are assumed to be manufactured in Hyderabad (760km), panels from BHEL or Tata-BP factory in Bangalore (372km), recycled in Poseidon Solar in Chennai (160km) and inverter and charge controllers from Su-kam factory in Delhi (2340km).

The output figures of such a study are EPBT (Energy Payback Time), Energy footprint and the equivalent CO2 emission factor GHG (Greenhouse Gas emissions).

Energy footprint per unit $\left[\frac{\text{kwh}}{\text{kwh}}\right]$

$$= \frac{\text{Total footprint of energy produced [kWhp] x thermoelectric conversion rate [0.35] /}}{\text{Annual energy consumed kWh}_{el} \text{ x 20 [years]}}$$

Payback period

$$= \frac{\text{Total footprint of energy produced [kWhp] x thermoelectric conversion rate [0.35] /}}{\text{Annual energy consumed kWh}_{el}}$$

Carbon Footprint per unit $\left[\frac{\text{kgCO}_{2eq}}{\text{kWh}_{el}}\right]$

$$= \frac{\text{Total carbon footprint of energy produced [kgCO}_{2eq}\text{]}}{\text{Annual energy consumed kWh}_{el} \text{ x 20 [years]}}$$

As some systems import all the energy needed from the grid, there is a loss of energy in conversion and transmission from the plant, as well as CO2 emissions when the energy is produced. Hence, it can be argued that this energy can never been paid back. It is also the case when facilities have high Grid Utilization Factor and low Solar Utilization Factor. In these cases, the value obtained for EPBT will correspond to a negative externality (more than 20 years).

In the case of on-grid systems, the annual electricity import from the grid has been taken for each site from the TNEB website (TNEB, 2013). In case of a SPV system, the energy generated is from Wattmon data over one year (when available). If not available through the Wattmon, it has been calculated according to the following formula:

$$E = P \times 24 \times 365 \times CUF$$

Where

- E = energy generation per annum in kWh
- P = power of the system, viz. number of panels x wattage
- CUF or Capacity Utilisation Factor = coefficient of efficiency of the system, taking into account the efficiency of the panels and inverter and hours of sunshine. For the study, the CUF is assumed to be 17%.

Note: Embodied energy is expressed in form of primary energy (kWh_th or kWh(p)), since most of the energy input is in the form of process (lower-grade) thermal energy. For the sake of clarity, all electrical inputs are converted into primary energy requirements, assuming a best thermoelectric conversion efficiency of 35%. Data used for calculations of embodied energy and emission factors are given in Annex 3.
Energy footprint, quantity of CO2 emitted (in kg equivalent of all greenhouse gas emitted) per kWh produced by the system and EPBT for each installation are presented in the table and graph below.

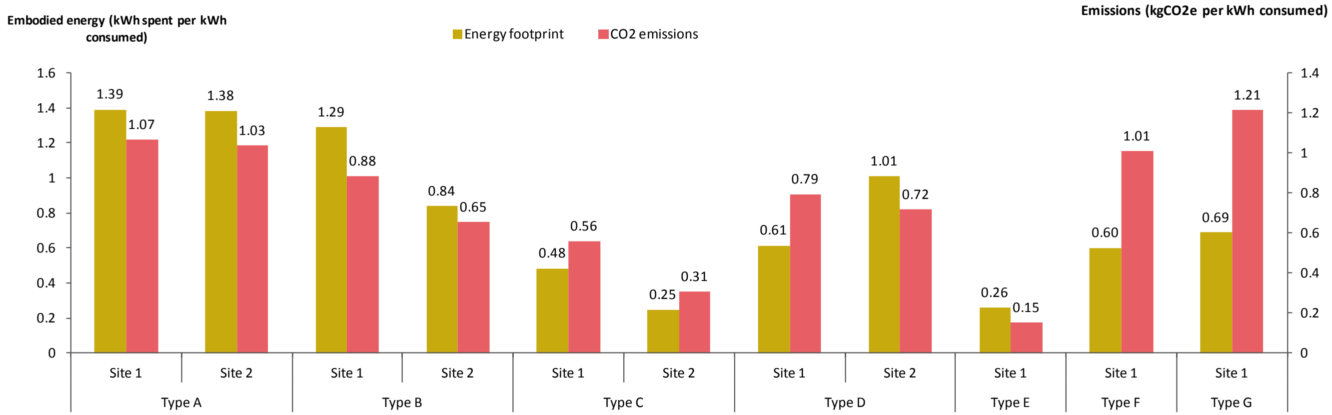


Figure 2.11

Few comments have to be made in order to explain some unexpected disparities between 2 systems of the same type.

- Type B: Site 1 has a SUF of 11% whereas Site 2 has SUF of 50%. The balance is provided by the grid. The fact that the solar system is underused in the case of Site 1 creates a negative externality in terms of energy footprint and high emissions per kWh.

- Type C: Site 1 has unexpected high values of energy footprint and CO2 emissions. This is due to the fact that the area of panels is high but wattage is low (the panels are old). The energy spent on manufacturing depending on the area of panels installed, resulting in high energy footprint for low production of energy, causing high EPBT. Site 2 seems more representative of a common stand-alone SPV system.

- Type D: Site 2 GUF is abnormally high for a back-up energy (33%), leading to an underuse of the solar system. This could be because the batteries are too small to ensure energy supply to the loads during absence of sunlight, hence the grid is often used as primary source. This leads to high energy footprint and CO2 emissions.
- The solar system of Type F is not sufficient to avoid an import from the grid (with a GUF of 40%), therefore causing high energy footprint and CO2 emissions.

Site reference	Energy footprint (kWh per kWh produced)	CO2 emissions (kg(eq) per kWh produced)	EPBT (yrs)	Average per type	
Type A	Site 1	1.39	1.065	27.8	27.74
	Site 2	1.38	1.035	27.7	
Type B	Site 1	1.29	0.883	25.8	21.27
	Site 2	0.84	0.655	16.8	
Type C	Site 1	0.48	0.559	9.7	7.31
	Site 2	0.25	0.307	4.9	
Type D	Site 1	0.61	0.794	12.3	16.23
	Site 2	1.01	0.716	20.2	
Type E	Site 1	0.26	0.152	5.2	5.18
Type F	Site 1	0.60	1.009	12.0	12.01
Type G	Site 1	0.69	1.213	13.7	13.75

Table 2.7

Conclusions of this study are the following:

- On embodied energy
  The manufacturing of a solar system is extremely energy-intensive, particularly in case of stand-alone SPV system which requires more battery storage. In case of a typical stand-alone SPV system (type C), 73% of the embodied energy is divided between manufacturing of batteries (52%) and of PV cells (21%). In case of a grid-connected system with batteries (type F), 46% of the embodied energy is induced by manufacturing PV modules and only 28% by battery manufacturing.

- About overall system relevance, from the worse performance to the best:
  As expected, Type A system requires more than 1kWh of energy for each kWh consumed as the energy source is not green. However, the CO2 emissions are lower than in case of use of diesel generator. The use of Type B system (grid supply with solar backup) does not seem relevant because the energy invested on manufacturing the solar system is partly wasted, as the system is underused. Type C shows satisfying energy footprint (~0.3kWh per kWh produced for normal wattage of panels) and very low CO2 emissions. Only transportation of SPV components caused these emissions. Type D system is slightly better because solar is the main source, but in case of low SUF, it is not so relevant either. In Type G, the use of the diesel generator has huge impact on CO2 emissions. Logically, the more the energy produced by the solar system, the less are the emissions per kWh of electricity consumed. Type F shows still high energy footprint and CO2 emissions in this case, induced by the consequent import from TNEB grid. As expected, the best system seems to be Type E. Absence of battery results in low embodied energy of solar, which is anyway paid back by a huge production and export. Solar energy exported to the grid compensates the emissions and energy footprint induced by import from the grid.

The main conclusion of this section is that the systems selected for the study are very varied, and have too characteristics specific to each installation on order to effectively compare them with each other. Hence, the same life-cycle analysis was reconducted on theoretical standardised systems, with a standard set of components.

Standardized systems

As cited above, the same methodology has been used to compare all the types of systems with the following assumptions. Changing any of these assumptions will change the final conclusions of the study.

- Systems have been sized for an annual consumption of 1500kWh. Panels are sized accordingly (total wattage is 1.2kW). For Type B system, which only uses solar system to charge the batteries, the required installed power is of 480W. Inverters are all of 1.4kVA.
- For stand-alone systems (Type C), batteries are sized to supply the loads for 12 hours; for solar backed-up systems (Type B), there are sized to supply power for 5/6 hours; for grid-connected, grid backed-up and grid-supplied systems (Type A, D, E, F, G), batteries are sized for 2 hours. Batteries are all of FLA type.
- Solar backed-up system (Type B) has SUF of 20%. Solar system with grid back-up (Type D) has SUF of 90%. Grid-connected system without battery (Type E) exports 10% of the annual consumption. Grid-connected systems with battery (Type F&G) exports 5% of the annual consumption. Therefore the import from TNEB is considered as null for grid-connected systems.

LCA analysis of these standard systems resulted in the following:

Type of system	EPBT (yrs)	Energy footprint (kWh/kWh)	Emissions (kgCO2e/kWh)
Type A	27.8	1.39	1.042
Type B	24.4	1.22	0.995
Type C	5.9	0.29	0.449
Type D	6.3	0.31	0.280
Type E	2.8	0.14	0.097
Type F	3.6	0.18	0.185
Type G	5.6	0.28	0.312

Table 2.8

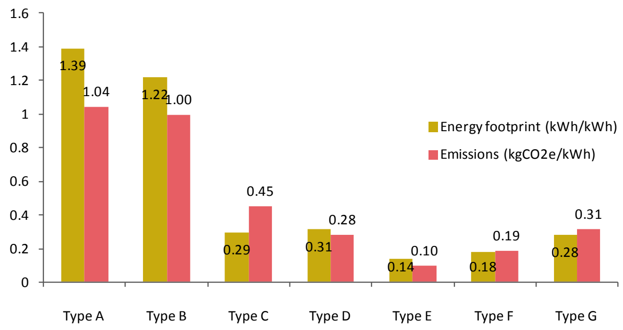


Figure 2.12: Energy footprint and emissions of standardized systems

General conclusions remain the same but figures are more accurate to compare the systems. An important adding of this section is that a system supplying 90% of the consumption with solar and 10% with grid (Type D when grid is actually used only as back-up to charge the batteries) has much lower emissions than a stand-alone. This is due to the fact that batteries can be undersized if grid is used as a back-up, in which case importing from grid is less polluting than having huge battery back-up. To complete this study, impact of connecting remote areas to the grid in order to transform Type

C into Type F should be studied, to determine if this investment is environmentally worthwhile.

System type / Ranking	Type A	Type B	Type C	Type D	Type E	Type F	Type G
Energy footprint	7	6	4	5	1	2	3
Carbon emissions	7	6	5	3	1	2	4
Final ranking	7	6	5	4	1	2	3

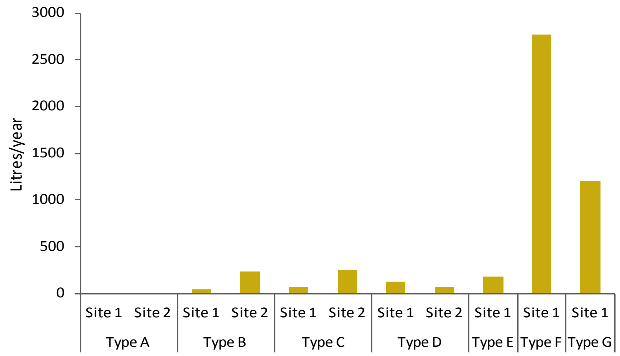
Table 2.9: Overall ranking on environmental parameters

Water consumption

Stand-alone SPV systems as well as grid connected SPV systems need water for the cleaning of panels. It has been estimated that coal-fired power plants use up to 92 litres of water for each unit or kWh of power produced (Jones, 2008). The River Network's 2012 paper estimates water used directly in photovoltaic power generation at around 0.11litres per kWh, which is on one hand far better than any of the fossil fuel equivalents and on the other hand, not zero (Solar Energy Industries Association, 2010). For the SPV panels to work at their best efficiencies, the panels must be clean. The table below shows the water used to produce 1 unit of electricity from solar panels as opposed to 1 unit of electricity from fossil fuel powered power plants per SPV type configuration.

Land requirement

Stand-alone SPV systems as well as grid connected SPV systems have a land footprint. One kW of Solar PV panels requires 12m2 of space (Solar Mango, 2014). Panels of 3 buildings are ground mounted; indicating that 133.5m2 of ground space has been utilized. The following table assesses the specific land requirement for each site.



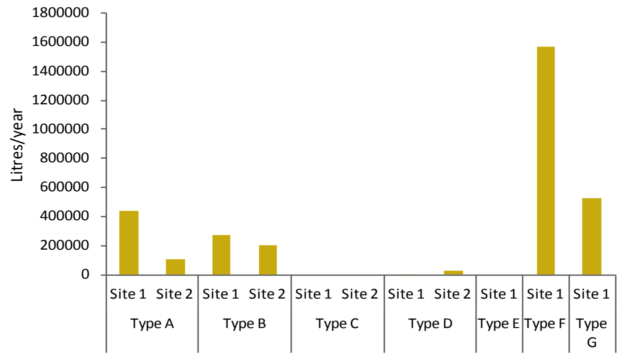


Figure 2.13: Water required for SPV system (above) and for fossil fuel power plants (below)

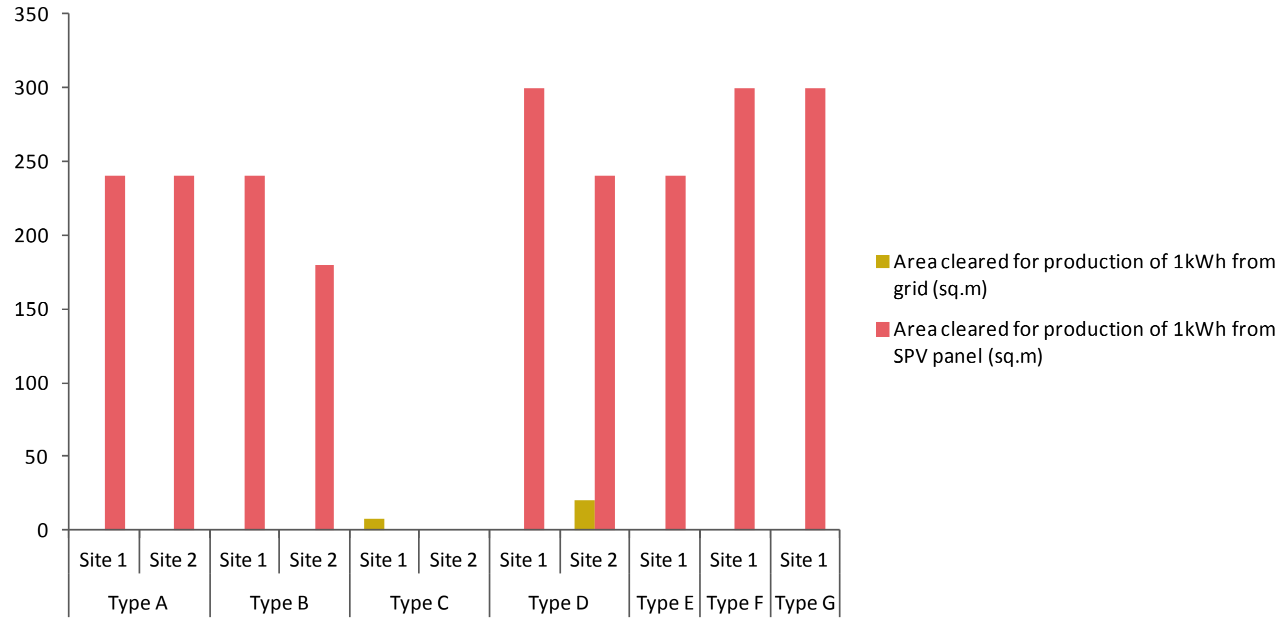


Figure 2.14: Land footprint of the different systems

Site reference		SPV mounting type	Distance to nearest LT Pole (mts.)	Area cleared for overhead grid connection (m2)	Area cleared for mounting the SPV panel (m2)
Type A	Site 1	None	40	240	0
	Site 2	None	40	240	0
Type B	Site 1	Roof mounted	40	240	0
	Site 2	Roof mounted	30	180	0
Type C	Site 1	Ground mounted	278	0	7.5
	Site 2	Roof mounted	40	0	0
Type D	Site 1	Roof mounted	50	300	0
	Site 2	Ground mounted	40	240	18
Type E	Site 1	Roof mounted	40	240	0
Type F	Site 1	Roof mounted	50	300	0
Type G	Site 1	Ground mounted	50	300	108

Table 2.10

The clearing and use of large areas of land for solar power facilities can adversely affect native vegetation and wildlife in many ways, including loss of habitat; interference with rainfall and drainage; or direct contact causing injury or death. The impacts are made worse when the species affected are classified as sensitive, rare, or threatened and endangered. Land degradation is a process in which the value of the biophysical environment is affected by a combination of human-induced processes acting upon the land. Construction of solar facilities on large areas of land requires clearing and grading, and results in soil compaction, potential alteration of drainage channels, and increased runoff and erosion.

Conclusion

Grid-connected solar systems have a clear advantage on technical, economical, social and environmental parameters. They guarantee an efficient use of energy, low cost per kWh delivered, a short pay-back period of the energy used to manufacture the system and high level of comfort with lesser impact on lifestyle. To make a distinction between them, unless power has to be absolutely 100% reliable and available over time, diesel generator should be avoided due to the high amount of greenhouse gas it emits. The addition of batteries to a grid-connected solar system makes it more comfortable and less dependent on grid availability. As the back-up capacity needed is lesser than in case of a stand-alone system, the impact on the environment is still quickly paid back by the export of green energy to the grid.

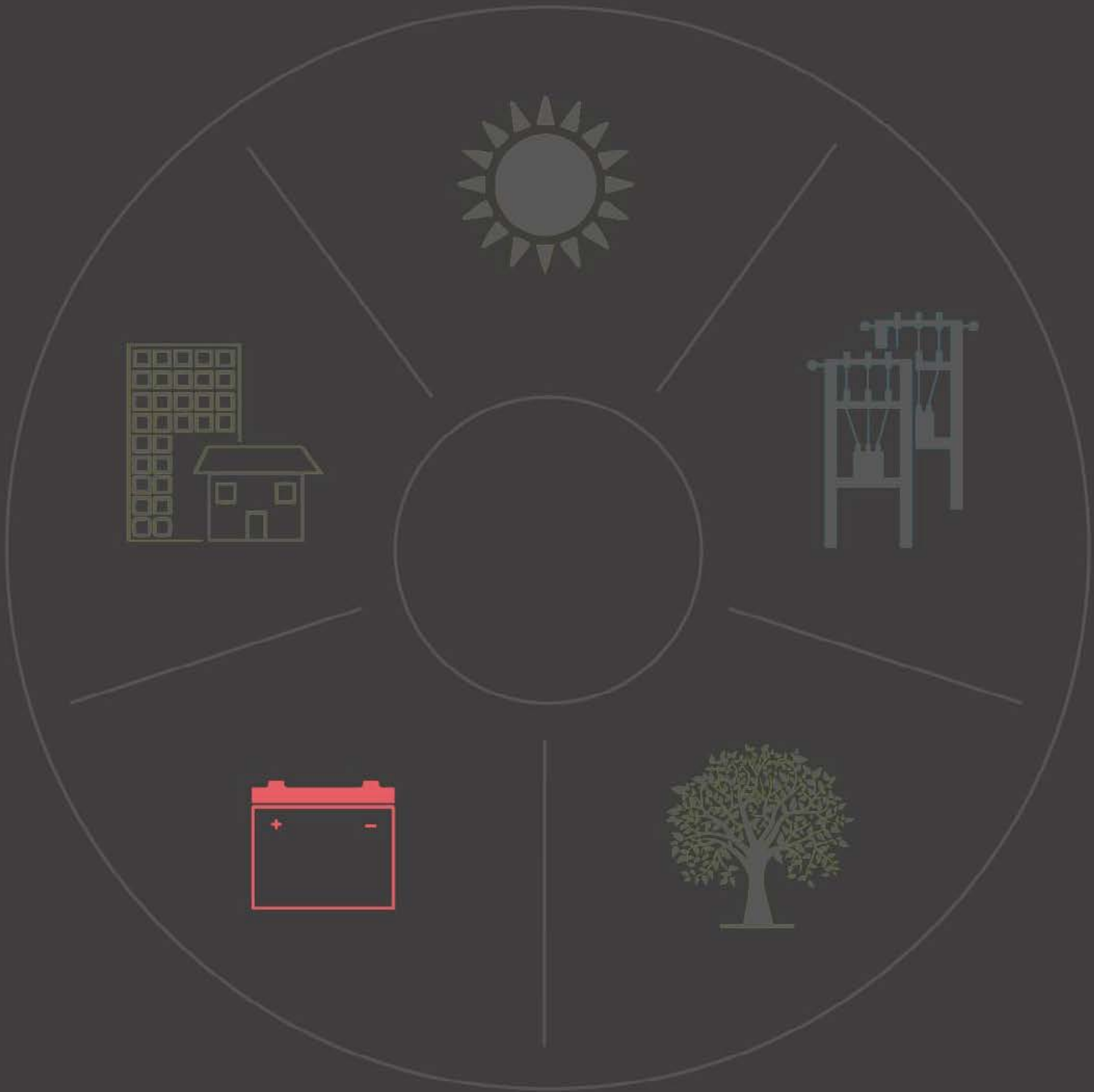
System type / Ranking	Type A	Type B	Type C	Type D	Type E	Type F	Type G
Technical	4	3	5	4	2	2	1
Economical	2	5	7	4	1	3	6
Social	4	4	5	4	3	1	2
Environmental	7	6	5	4	1	2	3
Final ranking	5	6	7	4	1	2	3

Table 2.11

The next part of this SPV study will focus on a comparison between different types of batteries, in order to recommend the best combination of type of system and type of batteries for Auroville, according to technical, economical, social and environmental parameters.

CHAPTER 3

A comparison of two battery chemistries



3

A COMPARISON OF TWO BATTERY CHEMISTRIES

Introduction

The scope of this study is to make a recommendation on the type of battery that can be considered to replace old batteries in Auroville buildings. It focuses on sites without a grid connection, i.e. buildings in the Greenbelt.

All the batteries currently in use in the buildings are of the lead acid type, and a great majority of them of flooded lead acid type. This is due to their low cost, possibility for long deep-cycle discharge and good performance in hot climates. We will study whether it is worthwhile to replace the existing Flooded Lead Acid batteries with either the Valve-Regulated Lead Acid batteries or Li-ion batteries by considering technical, economic, social and environmental parameters.

For the purposes of this study, we will make a distinction between two types of lead acid batteries: Flooded Lead Acid batteries (henceforth referred to as “FLA”) and Valve-Regulated Lead Acid batteries (henceforth “VRLA”). The chemistry of the two types does not change; they differ in the way the electrolyte is contained (either open or sealed) and how the gases are recombined. VRLA batteries are further subdivided into 2 types: Absorbed Glass Mat (AGM) and Gel, depending on the state of the electrolyte.

Technical parameters

The technical parameters used to compare the batteries are safety, thermal runaway, lifetime and performance.

Safety:

A quick charging process of lead-acid batteries emits hydrogen in the battery storage room, and also electrolyzes the water in the case of excess charging. There is a risk of ignition and explosions, and hence, it is recommended that other electrical or electronic systems are not co-located in the storage area. Due to the emission of gases, FLA batteries need to be stored in a properly ventilated room (http://akeinc.com/news/offgrid).

VRLA cells recombine the emitted hydrogen and oxygen, which produces water and prevent water loss. VRLA batteries have the advantage of being sealed cells: this prevents the electrolyte from leaking out, they do not need a specific ventilation to prevent accumulation of emitted gases, and they do not need routine maintenance. VRLA batteries have valves as a safety vent that releases gases generated from overcharge or rapid discharge (http://www.trojanbatteryre.com/). Unlike the lead acid batteries, Li-ion batteries do not produce gasses during use. They are sealed batteries, and do not need any routine maintenance (http://electronics.stackexchange.com). Li-ion batteries also occupy less volume than Lead Acid batteries, which can be an asset.

Thermal runaway:

Both lead acid and Li-ion batteries are capable of going into "thermal runaway" in which the cell rapidly heats up resulting in emission of dangerous fumes, electrolyte and flames. The probability and consequences of thermal runaway is theoretically higher for Li-ion batteries because of their higher energy density.

Manufacturers Li-ion batteries are taking sufficient precautions to prevent such events. This includes short-circuiting the charging process in case of overheating, and the use of Lithium Ferro Phosphate (LFP) cathodes. LFP reduces the self-heating rate during thermal runaway, and does not produce oxygen even when fully decomposed at high temperatures, which makes them the most resistant to thermal abuse (The Electrochemical Society Interface, summer 2012). LFP has a low self-heating rate, and the onset temperature for thermal runaway is higher than other Li-ion battery technologies (https://www.electrochem.org/).However, studies conducted by the Battery Power Magazine (www.batterypoweronline.com) show that stray incidents of thermal runaway in Li-ion batteries still occur.

Life cycle:

Lead acid batteries have significantly lower life cycles than Li-ion batteries in deep cycle discharge. The life cycle of any battery type can be increased by controlling the temperature and depth of discharge; however, lead acid batteries are generally more sensitive to these factors.

Life cycle in moderate climate:

The Life Cycle in a moderate climate (average temperature of 25^{o}C) for a VRLA-AGM battery and a Li-ion battery is shown in Figure 1. This shows that a VRLA battery (AGM) must operate at 30% depth of discharge to get a comparable life cycle as that of Li-ion battery operating at a 75% depth of discharge.

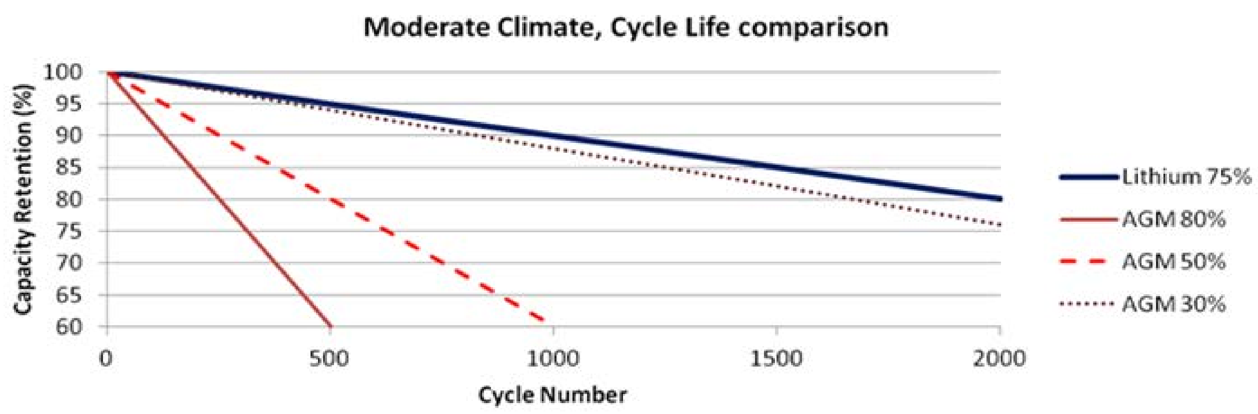


Figure 3.1

Life cycle in hot climate:

Figure 3 compares the life cycles of the two battery types in a hot climate (average temperature of 33ºC). In a hot climate, the Life Cycle for a VRLA-AGM battery drops to half of its rating in moderate climate, while the Li-ion battery remains stable (till the temperature reaches 50ºC). This indicates that for two batteries of similar size, the Li-ion battery will have stored about 6 times more energy than a VRLA-AGM battery, before its capacity retention drops below 60% (Albright , Edie, & Al-Hallaj, 2012).

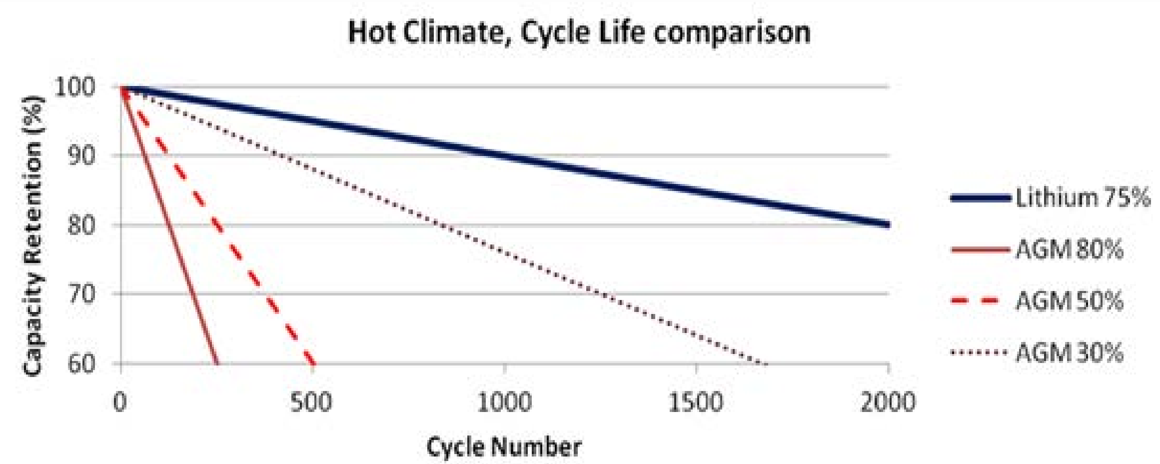


Figure 3.2

Considering that lithium-ion is able to function at a higher depth of discharge than lead acid batteries (especially when being used in deep-cycle), the batteries can be undersized for the same capacity.

Life cycle of batteries in Auroville:
There is no clear-cut method of determining the number of cycles a battery has completed (or the number of charge cycles a battery can still deliver). Condition of two batteries (and the balance life) could be determined by measuring voltage and specific gravity. However, as batteries are not always used in deep cycles, it is difficult to ensure that the battery is fully charged (or fully discharged) when measuring voltage. Also a hydrometer can be used to measure specific gravity, but this will not work on VRLA batteries since they are sealed. Health of the battery could also be measured in determining power delivered by the battery in one full discharge cycle or one full charge cycle. However, each of these measures shortens the battery life.
As a result, for the purposes of this study, we considered the age of the batteries as an indicator of the health of the battery. Given the type of use in Auroville, Rama (of Solar Service) recommends changing FLA batteries every 3-4 years. Sunlit Future have been installing VRLA batteries from Amara Raja, and these are generally lasting 6 years. Lithium-ion batteries have not yet been installed in Auroville. However, given that they are less sensitive to usage factors (such as state of charge during use, excessive charging or discharging, climate, etc.), we assume that they would last at least 10 years (as guaranteed by the manufacturer).

The table below provides a quick glance of batteries in 5 communities in the Greenbelt, viz. Adventure, Samriddhi, Evergreen, Miracle and Discipline.

Battery Type	< 1 year	1-3 years	3-6 years	6-10 years	Unknown age	Total
Lead Acid (FLA)	2	4	5	1	17	29
Lead Acid (VRLA)		2			1	3
Lithium Ion (Li-ion)						0
Total	2	6	5	1	18	32

Table 3.1

Performance:

The following sections evaluate the performance of batteries based on charge time, discharge time, effects of idleness and energy efficiency.

Charge time:

The time a battery takes to charge from zero to full capacity is the Charge Time of the battery. In order to avoid heat build up, batteries should not charge too quickly. Higher amperage results in more heat, wearing the plates and sloughing off material, particularly when the battery is closer to full charge. Also, in VRLA batteries heat and overcharge will prevent proper recombination of gases emitted. (Richard Perez, Home Power).

Generally, FLA batteries should charge with a charging current of 1/10th of the global capacity (noted as C/10), VRLA batteries at a maximum charging current of 1/3rd of its capacity, noted as C/3 (http://www.power-stream.com/SLA-fast-charge.htm) and Li-ion batteries at a maximum charging current of 1C.

If we consider a 100Ah battery of different types, then the time taken to charge is given below.

Battery Type	Capacity(C)	Recommended	Time to charge
Charge current (A)	Time to charge		
Lead Acid (FLA)	100Ah	C/10 = 10A	100/10 = 10 hours
Lead Acid (VRLA)	100Ah	C/3 = 33.3A	100/33.3 = 3 hours
Lithium Ion (Li-ion)	100Ah	1C = 100A	100/100 = 1 hour

Table 3.2

The table above shows that for a battery size of a given capacity, the Li-ion battery will charge the fastest, and FLA battery will charge the slowest. This has particular relevance to buildings without a grid connection. Batteries get drained over night, and if the battery can charge quickly, then the battery reaches full capacity in the early part of the day, and will function at a higher state of charge for the rest of the day. This helps in preserving and prolonging the life of the battery.

Discharge rate:

Discharge rate is a “measure of the rate at which a battery is discharged relative to its maximum capacity”. It is often expressed as a rate of capacity (C-rate); a rate of 1C means that a 100Ah battery will discharge at 100A, effectively discharging it in 1 hour. A rating of C/2 implies that a 100Ah battery will discharge at 50A, and hence will take 2 hours to discharge. (http://web.mit.edu/)

The figure shows how long batteries take to discharge a certain percentage of their capacity. A 100Ah lead acid battery will only deliver 80Ah if discharged over 4 hours. In contrast a 100Ah lithium-ion battery will deliver 92Ah during a 30-minute discharge period. (Albright, Edie, & Al-Hallaj, 2012). As per the figure above, a VRLA

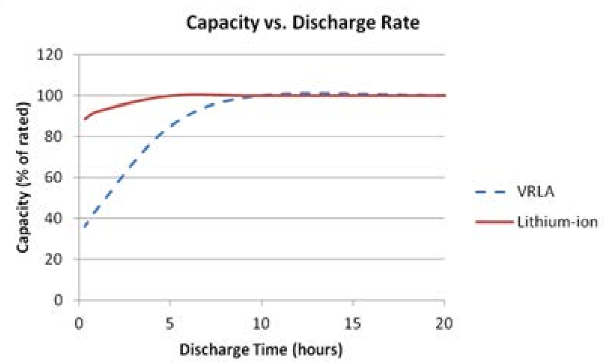


Figure 3.3

battery needs about 9 hours to deliver 100% of its capacity, while Li-ion battery will need 5 hours to give 100% of its capacity. In other words, in one hour, the VRLA battery gives only 10% of its capacity (which corresponds to its discharge rating of C/10), while the Li-ion battery gives more than 90% of its rated capacity. This means that if a high discharge rate is needed in a short interval of time, then Li-ion batteries are better suited for the purpose.

In the case of stand-alone solar photovoltaic installations (those most common in the Greenbelt), the batteries charge during the day (mostly in the first half of the day). In offices, the batteries discharge slowly during the day, while in residences, batteries discharge mostly after sunset. In Akash's (Cynergy) experience, consumption loads in Auroville rarely draw more than 70A and do not need a discharge rate quicker than C/5, even if the building has an air conditioner. As a result Li-ion batteries might not be called for. For instance, if we consider a household in the Greenbelt using 2 tube lights, 3 fans, 1 TV and 1 laptop, it amounts to 550W. The formula below allows us to calculate the ideal discharge rate.

$$\text{Discharge rate (A)} = \frac{\text{Load (W)}}{\text{Inverter voltage (V)}^{1}}$$

Considering an inverter of 12V, we get a discharge rate of 550/12 = 46A. If these loads are powered on simultaneously over 3 hours, then a capacity of 140Ah will be needed. As per the graph above, this can be delivered in 3 hours by a 200Ah VRLA battery (140Ah rep-

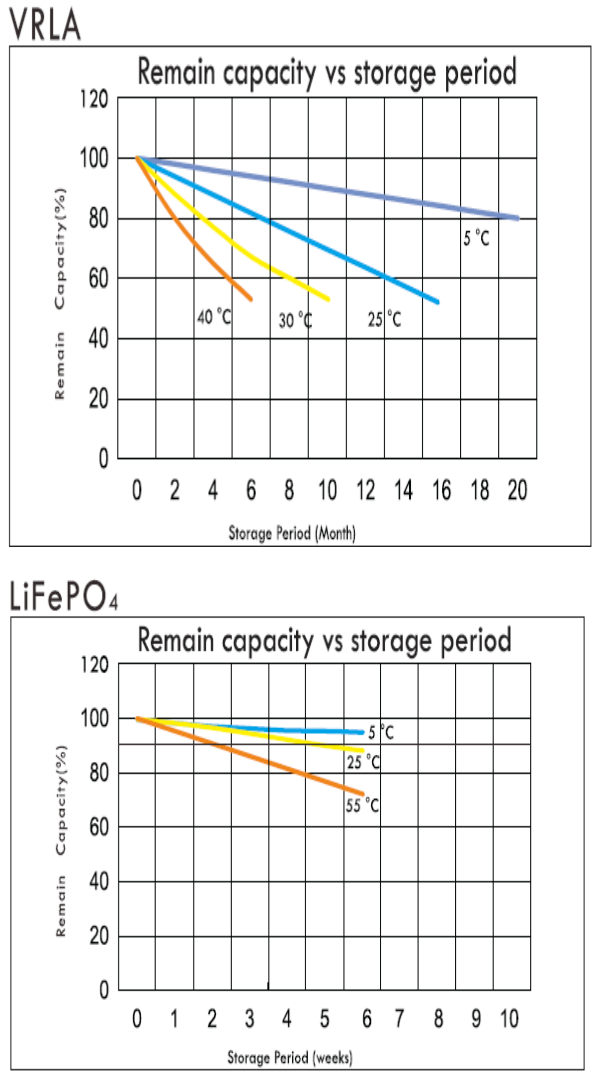


Figure 3.3

[1]This is derived from the formula Required power x required back-up hours = inverter voltage x battery capacity (http://ksetu.hubpages.com)

resenting 70% of its capacity), and the high performance rating of Li-ion is not necessary.

Effects of idle time:

Batteries of all three types (FLA, VRLA and Li-ion) lose their charge if kept idle over a period of time. The actual rate of self discharge is debated; according to MPowerUK lead acid batteries lose 4 to 6% of their energy per month when not in use, while Li-ion batteries lose 2 to 3% (http://mpoweruk.com/performance.htm). It is recommended that lead acid batteries be kept 80-100% full in idle storage; Lithium-ion batteries can be stored at any state of charge (http://www.progressivedyn.com).

Since most batteries in Auroville are of the FLA type, residents need to take proper precautions when travelling over extended periods. After 6 months at 40°C, VRLA batteries lose about 50% of its initial capacity (6-8% per month), while the Li-ion battery loses less than 40% even if temperatures cross 500C. It can be deduced that if the storage temperature was 400C, then the energy loss in the Li-ion battery would have been around 20%, i.e. approximately 3% per month (Carsten, Auroville Energy Products).

Energy efficiency:

Energy efficiency can be defined as "using less energy to provide the same service" (http://eetd.lbl.gov/ee/ee-1.html). In the case of batteries this can be calculated as the ratio of total energy supplied by a battery for every unit of energy that is used to charge it. There are usually energy losses, and the efficiency also decreases with the state of charge - the higher the depth of discharge, the lower the efficiency (solarfacts.com).

Battery efficiency in Auroville has been measured in 8 sites, according to the protocol described in Part 1. Figures obtained are given below.

SPV configuration	Site	Battery type	Battery efficiency
Type A	1	FLA	42.0%[2]
	2	VRLA	72.9%
Type B	1	FLA	75.3%
	2	FLA	71.8%
Type C	1	FLA	70.3%
	2	FLA	71.1%
Type D	1	VRLA	79.5%
	2	FLA	75.9%
Type E	1	Not applicable	Not applicable
Type F	1	VRLA	Data not available
Type G	1	FLA	Data not available
Average			73.8%

Table 3.3

[2]This very low value is not considered as representative, as it is due to a dead battery that has not been replaced yet.

Lead acid batteries in Auroville have an average efficiency of 74% while in use, with the average efficiencies of 72.9% for FLA and 76.2% for VRLA Tests confirm the empirical values admitted for lead acid batteries. Tests on Li-ion batteries have been conducted by Auroville Energy Products and show efficiency above 90% (Carsten, Auroville Energy Products).

Summary

The following table provides a summary of the technical parameters. Li-ion batteries are technically superior to the lead acid batteries for their high performance and safety. If high charge and discharge rates are not required, then VRLA batteries can be recommended.

Type/Parameter	FLA	VRLA	Lithium-ion
Weight of a 100Ah, 12V battery	23 kg	31 kg	14 kg
Gas emission	Oxygen & hydrogen	Gases are recombined & vented	No gas emission
Expected no. of cycles	1200 cycles @ 50% DoD	2000 cycles @ 50% DoD	3000-5000 cycles @ 80% DoD
Advised maximum discharge rate	C/20	C/5	C
Efficiency in Auroville	72.9% (measured)	76.2% (measured)	>90%

Table 3.4

Economic parameters

This section compares the Levelised costs of different batteries by comparing the cost per kilowatt-hour supplied by each battery type over its lifetime, using the following assumptions:

- Batteries are sized for different depths of discharge, according to manufacturer specifications; lead acid batteries are considered at 50% DoD, while Li-ion batteries are considered at different depths of discharge.
- Batteries are chosen from the same manufacturer as far as possible to do justice to the comparison viz. FLA and VRLA batteries from Amara Raja and Li-ion batteries form Smart Battery
- Efficiency is assumed to stay constant over the battery's lifetime (even though in actual fact, the efficiency of lead acid batteries progressively decreases over time, while efficiency of Li-ion batteries stays steady).

Gross and net cost per kWh delivered over the lifetime is calculated as follows:

Gross cost per kWh

$$= \frac{\text{Cost of battery + Maintenance cost}}{\text{Gross kWh delivered over lifetime}}$$

Net cost per kWh

$$= \frac{\text{Cost of battery + Maintenance cost}}{\text{Net kWh delivered over lifetime}}$$

Where,

- Gross kWh delivered over lifetime

  = Expected number of cycles x Depth of Discharge x Capacity

- Net kWh delivered over lifetime

  = Gross kWh delivered x Efficiency

The following page illustrates the results we obtained. Due to the high longevity and low cost, VRLA-AGM batteries (from Amara Raja) are by far the most economical option. Price per kWh of FLA is high because of their short lifetime and running costs. VRLA-Gel batteries allow a higher discharge rate but are relatively more expensive. Li-ion can be undersized due to higher DoD, but costs remain high. Based on the number of cycles a battery can deliver over its lifetime at a given DoD, figures show that Li-ion used at shallow DoD (50%) are a better investment than FLA and VRLA-Gel batteries. Using Li-ion at higher DoD shortens their lifetime and makes them uncompetitive compared to lead acid batteries.

However, this assumes that the Li-ion battery will run 8000 cycles, representing a life of 21-22 years, without break down. If an accident does occur during this period, and the battery system has to be replaced for any reason, then costs will double, and the batteries will prove to be uneconomical. If correctly sized and used with caution, Li-ion can effectively compete with FLA and VRLA-Gel costs on the long run.

Assumptions / Inputs	FLA	VRLA-AGM	VRLA-Gel	Li-ion (50% DoD)	Li-ion (75% DoD)	Li-ion (95% DoD)
Manufacturer	Amara Raja	Amara Raja	Amara Raja	Smart Battery	Smart Battery	Smart Battery
Voltage (V)	12	12	12	12	12	12
Energy storage capacity (Ah)	150	150	150	150	100	75
Average rate of discharge assumed	50%	50%	50%	50%	75%	95%
Cycles during life of the battery (nos)	1,200	2,000	2,000	8,000	4,000	2,000
Efficiency of the battery	75%	75%	75%	90%	90%	90%
Maintenance cost per cycle (INR)	1.10	0	0	0	0	0
Battery cost (INR)	15,000	18,900	26,460	1,14,000	78,000	60,000
Net energy output (kWh)	810	1,350	1,350	6,480	3,240	1,539
Maintenance cost during life cycle (INR)	1,320	0.00	0.00	0.00	0.00	0.00
Total life cycle cost of battery ownership (INR)	16,320	18,900	26,460	1,14,000	78,000	60,000
Cost per kWh of gross energy throughput (INR)	15.11	10.50	14.70	15.83	21.67	35.09
Cost per kWh of net energy output (INR)	20.15	14.00	19.60	17.59	24.07	38.99

Table 3.5

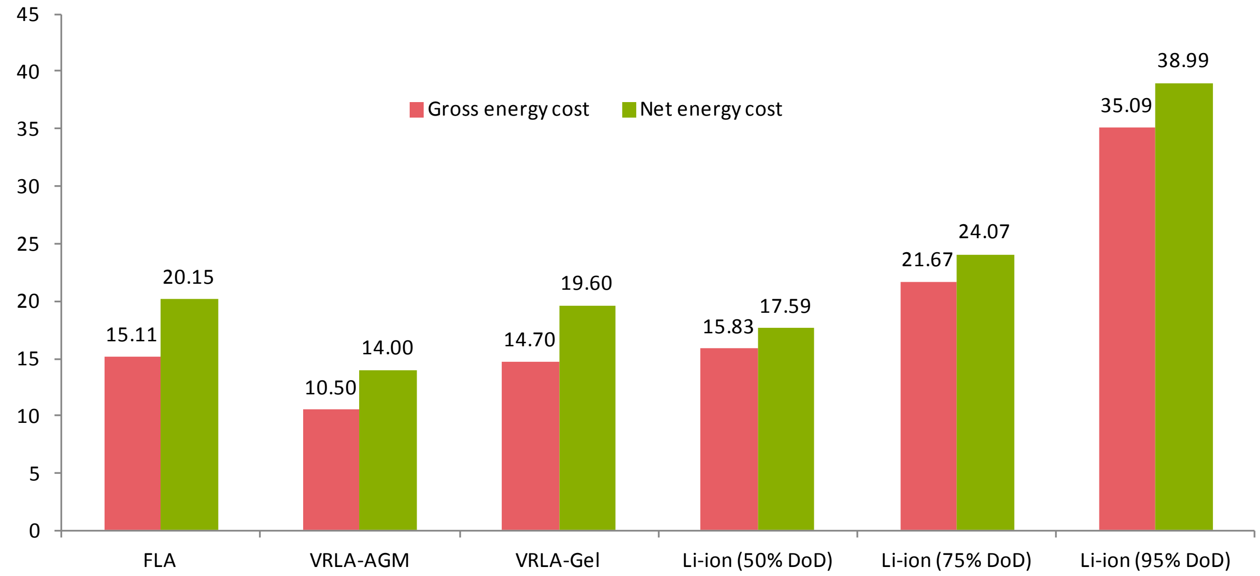


Figure 3.4

Levelised costs

For this section, the same configurations of energy systems (based on standardized characteristics) developed in Part 1 have been studied. Each type will have different Levelised costs over a lifetime of 20 years whether FLA, VRLA or Li-ion batteries are used for back-up. Batteries are assumed to be replaced 6 times for FLA (average lifetime is 3.5 years per battery), 4 times for VRLA (lifetime of 6 years) and twice for Li-ion (lifetime of 10 years). Figure above shows Levelised costs of the systems over 20 years, per kWh delivered. The graph shows that for systems which do not need high battery capacity (Type A, D, E, F & G), the price per kWh delivered does not change in significant proportion compared to the total cost of the system.

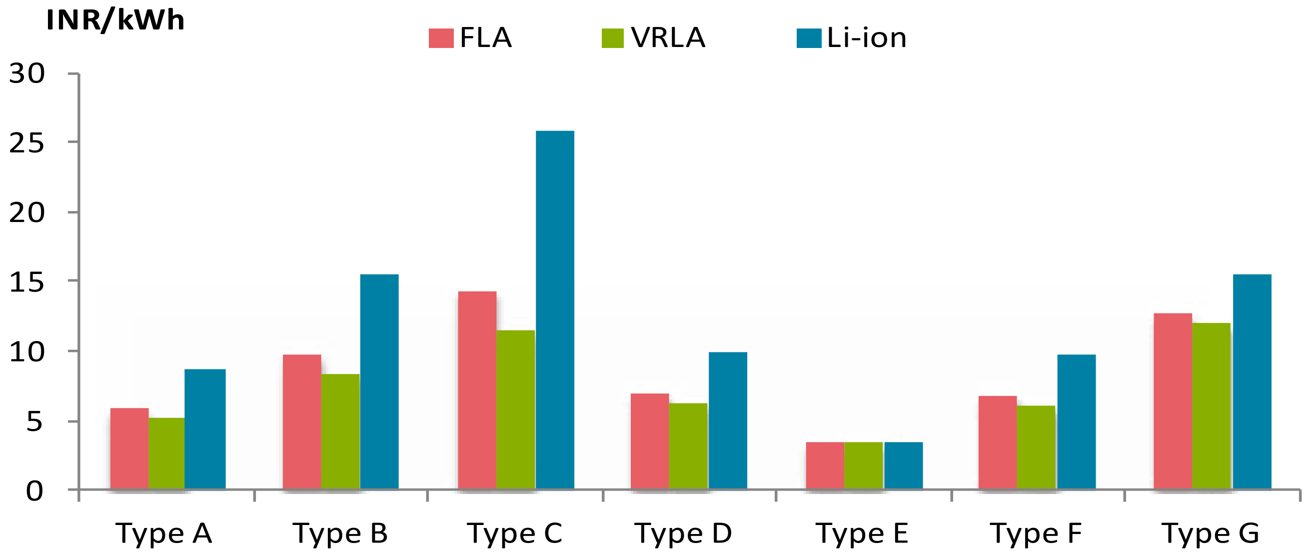


Figure 3.5

Summary

The 3 battery types of similar brands have been compared using different economic indicators: initial costs, cost of storage over lifetime of the battery as well as the cost of a system with different battery types. Due to fewer replacements needed over the life-time of the system and low cost, VRLA is the most economical option.

Parameter	FLA	VRLA (AGM)	Li-ion
Brand	Amara Raja	Amara Raja	Smart Battery
Initial cost	8.3 Rs/Wh	9.5 Rs/Wh	49 Rs/Wh
Cost of storage @ 50% DoD (net)	20 Rs/kWh	14 Rs/kWh	18 Rs/kWh
Total cost of stand-alone per kWh deliv-ered on a 20 years lifetime	14.3 Rs/kWh	11.5 Rs/kWh	25.9 Rs/kWh

Table 3.6

Social parameters

The social parameters used to compare the batteries are usage factors that impact on the lifestyle of the person, such as charging habits, top up charge, idle time and maintenance.

State of charge

To prolong the life of the batteries, the depth of discharge as advised by the manufacturer should be respected. For lead acid batteries (FLA and VRLA), the number of cycles is usually indicated for 50% depth of discharge; and the state of charge should not go below 80% depth of discharge. If the consumption load is high, then the charge level might drop below 50%, thereby dropping the voltage, which could adversely affect the connected devices. Consumption load should be consciously reduced.

On the other hand, Li-ion batteries provide for a higher depth of discharge (DoD) of up to 80%, which allows much more flexibility in its usage. The higher discharge rate allows more energy to be supplied during a short span of time. Also, lithium-ion batteries have a flat voltage curve in the usable discharge range. The voltage delivered between the 10-90% DoD is stable and this allows battery to be used up to a very shallow state of charge (Batteryuniversity.com and MPowerUK.com).

Sulfation

During use, small sulphate crystals are formed, which are normal and not harmful. However, if the batteries are kept idle for a prolonged period of time, the lead sulphate converts to crystalline deposits on the negative plates, which slows down the battery charging due to internal resistance. To avoid this phenomenon, a topping charge should be applied every month for lead acid batteries. Sulfation does not occur in the case of Li-ion batteries.

(http://batteryuniversity.com/learn/article/sulfation_and_how_to_prevent_it).

Loss of water

During use, and especially on overcharge, the water in the electrolyte splits into hydrogen and oxygen. The battery begins to gas, which results in water loss. In FLA batteries, distilled water needs to be added at regular intervals. Failure to do so can halve the life of the battery, and also affect its energy storage capacity. In sealed batteries, water loss leads to an eventual dry-out and decline in capacity. The initial stages of dry-out can go undetected and a drop in capacity may not be immediately evident. Early detection of this failure is important (http://batteryuniversity.com/).

Li-ion batteries in themselves do not require maintenance, but the proper functioning of the whole system (charge controller, etc) should be observed closely using a remote monitoring system. Since there is insufficient experience of Li-ion batteries in Auroville, and also considering the high setup costs, it is advised that pilot installations are closely monitored by qualified technicians.

Summary

A summary of the social parameters is presented below for reference. Li-ion batteries are the most practical and flexible to use, followed by VRLA and finally FLA.

Parameter	FLA (100Ah, 12V)	VRLA (100Ah, 12V)	Li-ion (100Ah, 12V)
Depth of discharge	Maximum depth of discharge: 50%	Maximum depth of discharge: 50%	Flexible to deep discharge: can be used up to 90% depth of discharge
State of charge	Charge should be kept above 80% to preserve lifetime	Charge should be kept above 80% to preserve lifetime	Can be operated at shallow charge
Storage while not in use	High self-discharge rate degrading performance	High self-discharge rate degrading performance	Low self-discharge rate; performance not affected
Type of storage room	Needs a ventilated room	Needs a shaded space (to avoid heat build-up)	Not applicable
Battery volume	0.0121 m3	0.0117 m3	0.0117 m3
Routine maintenance	Batteries should be topped with distilled water regularly	None	None
Charging maintenance	Full top up charge once a month	Full top up charge once a month	Full top up charge every 6 months

Table 3.7

Environmental parameters

In the following section, the two battery types are compared on the following environmental parameters: toxicity during the manufacturing process, recycling and total life span impact.

Toxicity during manufacturing

The manufacture of batteries causes air pollution as shown in the graph. Lead acid batteries emit more air pollutants than Lithium Ion batteries.

VOC: Volatile Organic Compounds
CO: Carbon Monoxide
NO_x: Oxides of Nitrogen
PM: Particulate Matter
SO_x: Oxides of Sulphur
CH_4: Methane
N_2O: Nitrogen Dioxide
CO_2: Carbon Dioxide
Source: Argonne Laboratory Report, Sullivan and Gaines

Lithium ion batteries are very resource intensive, requiring the mining of lithium, copper, aluminium and iron ore. However, the amount of lithium needed for a single battery system is relatively small compared to the batteries overall mass (3% of lithium out of total weight, versus 20% for lead in lead acid batteries). (Albright, Edie & Al-Hallaj, 2012).

Also, graphite is used only as the main host material of the anode in Li-ion batteries, while it is an additive in lead acid batteries (Roskill Information Services, 2013). The growing production of Li-ion batteries will potentially increase the demand for graphite, which could soon be in short supply. The process to purify graphite to 99.9% purity level also produces a great amount of waste and is energy-intensive. This is bound to receive increasing attention in the coming years.

Recycling

The battery recycling industry in India is dominated by small-scale and backyard recyclers. According to the Central Pollution Control Board, there are 353 registered recyclers for lead acid batteries in India with 14 of them located in Tamil Nadu. However most of these facilities are small and very few operate with sufficient pollution controls (Central Pollution Control Board, 2010). There are only 2 plants in India of an adequate size where pollution controls become cost effective (Occupational Knowledge International, 2010). Suryan, executive of EcoService and AuroScrap, mentions that the battery recycling facilities in Chennai and Pondicherry dispose of acid by dumping it in the gutters. Areas surrounding lead battery recycling centres experience higher lead exposures. Several studies have documented lead poisoning among children and residents in areas having lead battery recycling centres (Occupational Knowledge International, 2010).

Speaking to resource persons in Auroville, we gathered the following:

"I met with Iyyanar who deals with waste-battery collectors in this local area. He takes the batteries to where they are broken down for recycling. But those people are doing it illegally without following any kind of regulation. And they have a network of Gundas (Rowdies) that have political backups. He said that there are more suppliers that take the batteries and send them to Coimbatore, Trichy and Bangalore where the batteries are dismantled, but he himself is not sure if they follow the legal procedures."(Prakash, 2014)

"Every company has a policy to take back batteries but in principle no one buys back as transport to send batteries is very high. These VRLA batteries do not have acid in fluid state, they can only be opened by machines for which they are collected and bought by scrap dealers and send to factories where the lead is taken out. Most of the clients give the batteries to eco service and they in turn scrap it to the distributors and from there it goes to factories for recycling." (Rishi, 2014)

A study conducted by Occupational Knowledge (2010) found the following:

Very few manufacturers in India are meeting legal requirements to collect the old batteries. 90 per cent of the batteries are sold through dealers, and only a small percentage of the total number of batteries sold is being collected back by battery manufacturers, viz. Amara Raja (26%), TAFE (11%), Tudor (39%) and GNB (0%).

There is no central effort to collect information on compliance with the Battery Management and Handling Rules and there is no penalty for manufacturers who fail to meet the regulatory requirement.

The recycling process for Lithium ion batteries is complex and cost intensive, as it involves collecting, transporting, sorting, shredding, separating metallic and non-metallic substances, neutralizing hazardous substances, smelting, purifying and transforming the raw material again from ground zero. As a result, mining for the required raw material is currently more financially attractive than recycling. However, as finding sufficient raw material to satisfy the increasing demand becomes a challenge, recycling processes can be expected to gain momentum.

In Auroville, used batteries are usually stored for extended periods as there is a lack of recycling facilities close by. Storage of Lithium has much less environmental impact than lead acid batteries, as it is not toxic.

Total life span impact

Lead acid batteries are environmentally less friendly than lithium-ion batteries in hot climates. Lead acid batteries require several times the amount of natural resources as lithium-ion batteries for a given energy storage capacity, making them more harmful to the environment during the mining process (Albright, Edie & Al-Hallaj, 2012).

Researchers at Stanford University have computed the Energy Stored on Investment (ESOI) indicator. It is the ratio of the amount of energy a device stores over its lifetime to the energy needed to build the battery (Barnhart, 2013), calculated as follows:

$$\text{ESOI} = \frac{\text{Number of cycles x Efficiency of battery x Avg. Depth of discharge}}{\text{Energy used for manufactuing of 1kWh of battery}}$$

$$\text{ESOI}_e = \frac{C\lambda\eta D}{C\varepsilon_e} = \frac{\lambda\eta D}{\varepsilon_e} < \frac{\text{kWh}_e}{\text{kWh}_e} >$$

Where

- C is the capacity (it can be simplified in the equation: it figures in the numerator as a factor to calculate the total energy stored, and in the denominator as the energy used for building the battery is proportional to the capacity)

- λ is the number of cycles during the lifetime of the battery

- η is the efficiency of the battery
- D is the average depth of discharge of the battery during its use
- ε_e is the energy used to manufacture the battery per kWh capacity

In other words, the higher the ESOI index, the more worthwhile the investment.

The table below lists the median ESOI of different battery assessments. Lead acid batteries are usually sized for 50% DoD. The efficiency of lead-acid batteries is considered to be 75% in average.

Battery	Efficiency of the battery (η in %)	Number of life cycles at 33°C (λ)	Depth of discharge (D in %)	Embodied energy (εe)	Energy Ratio (ESOI)	No. of kWh spent for each kWh delivered
FLA	75%	1200	50%	96	4.69	0.213
VRLA	75%	2000	50%	96	7.81	0.128
Li-ion	90%	6,000	80%	136	31.76	0.031

Table 3.8

Lead acid batteries have a significantly lower ESOI ratio due their low life cycle. More energy is used in the manufacturing of Lithium-ion batteries but they have a longer life cycle, which increases the ESOI ratio. Even though the initial purchase price is higher than lead acid batteries, the table shows that over the full life cycle, Lithium-ion isa better investment.

Energy footprint and carbon footprint

In this section we re-visit the system configurations studied in Part 1, covering 7 different configurations, with or without PV, with special emphasis on stand-alone systems. We try to determine the impact of replacing the current FLA batteries with an equivalent VRLA or Li-ion battery. In order to do so, the embodied energy of the different batteries (per kWh capacity)is determined; next, an assessment of the global energy and emission savings in case of a change of battery type is calculated.

The main challenge is determining the embodied energy of batteries is the wide range of figures cited in different scientific publications. Embodied energy of manufacturing lead acid battery is taken as 331 kWh per kWh of battery capacity. To keep consistency in the choice of data, the emissions are considered to be of 60 kgCO2e/kWh of battery capacity, considering that manufacturing occurs in Asia. For Lithium-ion, embodied energy is 477 kWh per kWh capacity and emissions are of 90 kgCO2e per kWh capacity (Central Research Institute of Electric Power Industry, 2011).

Another assumption is that as lead is widely reused in India, the first battery is assumed to be manufactured from virgin materials (100% embodied energy and emissions induced). The next batteries are manufactured from reused lead (75% embodied energy and emissions induced). Technologies to recycle Li-ion are not available yet, but we will assume that the same savings of energy will be possible in 10 years (75% embodied energy and emissions when the second battery is manufactured).

The following figures of energy used to manufacture the batteries, and resulting emissions are obtained:

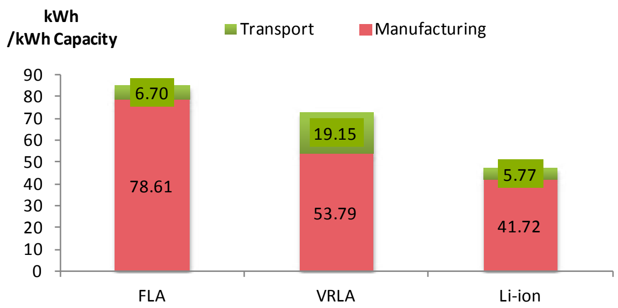


Figure 3.6

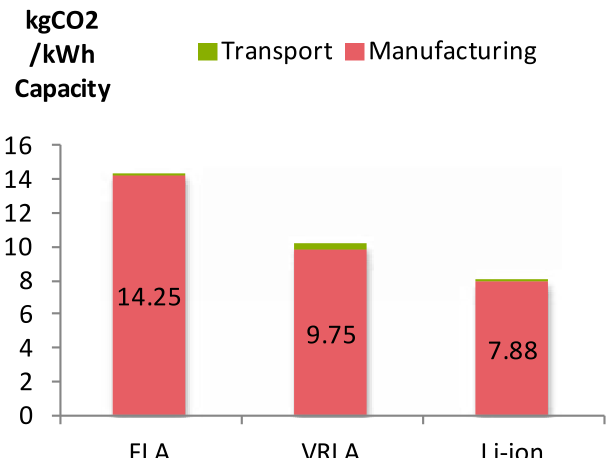


Figure 3.7

Using the above figures, the total embodied energy and carbon emissions over 20 years for a stand-alone SPV system is given below, where

- Type C-1 represents the first sample SPV system
- Type C-2 represents the second sample SPV system
- Type C-Standardized represents a standardized stand alone system

Swapping FLA batteries with VRLA batteries and Li-ion batteries would result in savings in both embodied energy and carbon emission As given in the following table.

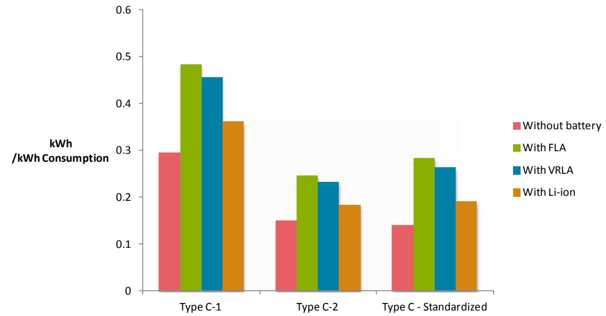


Figure 3.8

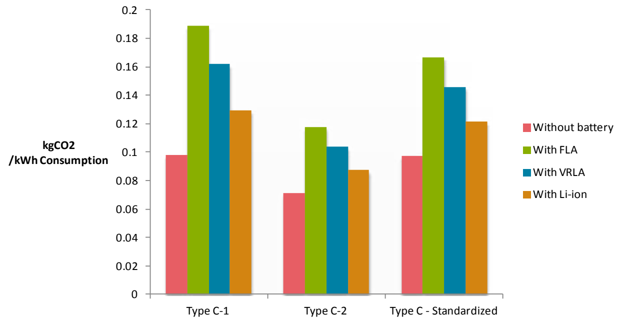


Figure 3.9

Energy and emissions savings	Site: Type C – 1	Site: Type C – 2	Site: Type C Standard-ized
Replacing FLA with VRLA batteries	0.0273 kWh/kWh 0.0268 kgCO2/kWh	0.0139 kWh/kWh 0.0137 kgCO2/kWh	0.0208 kWh/kWh 0.0204 kgCO2/kWh
Replacing FLA with Li-ion batteries	0.1226 kWh/kWh 0.0591 kgCO2/kWh	0.0626 kWh/kWh 0.0302 kgCO2/kWh	0.0935 kWh/kWh 0.0451 kgCO2/kWh

Table 3.9

Assuming 1500kWh is consumed annually, the annual savings from swapping FLA batteries with other battery types is given below:

Annual savings	Type C – Standardized stand-alone system	
Replacing FLA with VRLA batteries	31.2 kWh per year (7% gain compared to FLA)	30.6 kgCO2 per year (12% gain compared to FLA)
Replacing FLA with Li-ion batteries	140.2 kWh per year (33% gain compared to FLA)	67.6 kgCO2 per year (27% gain compared to FLA)

Table 3.10

Using the same approach, the following results are obtained for the other types of energy systems

Savings from swapping	A	B	C	D	E	F	G
FLA with VRLA (kWh per year)	7.8	15.6	31.2	7.8	-	7.8	7.8
FLA with Li-ion (kWh per year)	35.0	70.1	140.2	35.0	-	35.0	35.0
FLA with VRLA (kgCO2e per year)	7.7	15.3	30.6	7.7	-	7.7	7.7
FLA with Li-ion (kgCO2e per year)	16.9	33.8	67.6	16.9	-	16.9	16.9

Table 3.11

The gains are proportional to the battery capacity needed for each system. Replacing FLA batteries is not lucrative in case of systems using grid-supply (i.e. Types A, B & D) since most of the pollution is caused by energy production in power plants. However, in case of stand alone systems (i.e. Type C) or systems exporting green energy (i.e. Types F & G), replacing FLA batteries would ensure savings in energy as well as greenhouse gas emissions. Since Type C systems inevitably have the largest battery banks, the impact of replacement is maxim for this type.

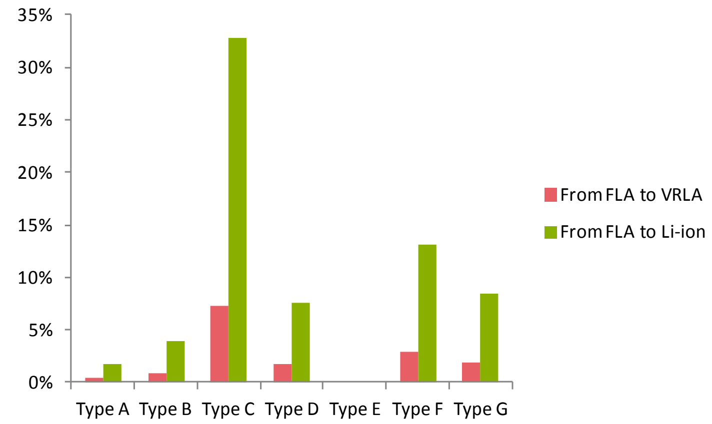


Figure 3.10

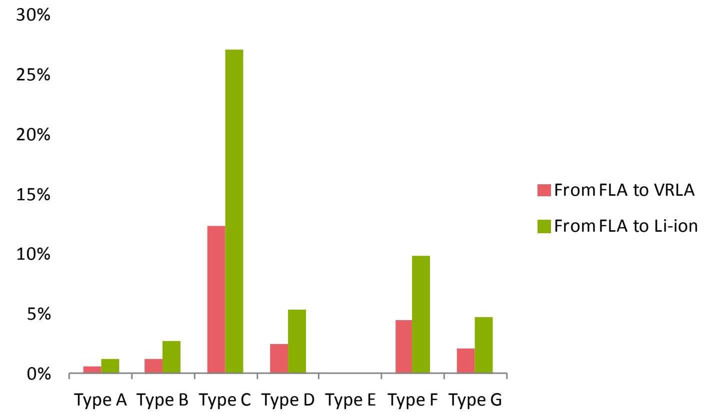


Figure 3.11

Summary

India needs to make progress with regards to battery recycling. Currently, lead is being re-used, but not in a clean and safe method; and Li-ion recycling facilities do not seem to be available in India as yet. Replacing FLA batteries with either VRLA or Li-ion batteries will minimize the pollution, especially of stand-alone systems.

Parameter	FLA	VRLA	Li-ion
Composition	20% of lead (toxic) of total weight	20% of lead (toxic) of total weight	3% of lithium (non-toxic) of total weight
Recycling	Lead can be recycled but in India, acid is usually dumped in the gutters	Lead can be recycled but in India, acid is usually dumped in the gutters	No recycling facility in India as yet
Storage	Toxic fumes emitted		Non toxic
ESOI	2.81	2.34	31.76
Environmen-tal gain from converting type of battery in stand-alone	N.A.	Swap from FLA to VRLA: 7% savings in energy 12% savings in green-house gas emissions	Swap from FLA to Li-ion: 33% savings in energy 27%savings in greenhouse gas emissions
Environmen-tal gain from converting type of battery in stand-alone	N.A.	Swap from FLA to VRLA: 7% savings in energy 12% savings in green-house gas emissions	Swap from FLA to Li-ion: 33% savings in energy 27%savings in greenhouse gas emissions

Table 3.12

Recommendations

Based on this research, as well as the other parts of the Energy Sourcing Study, the following interventions are considered:

Interventions at the Building level

- Replace FLA batteries with VRLA, when they finish their life
- Replace FLA batteries with Li-ion, when they finish their life
- Connect a grid interactive system (without battery backup) when the FLA batteries die

Interventions at a Community level

- Install centralized storage by community with VRLA
- Install centralized storage by community with Li-ion
- Connect a grid interactive system (without battery backup) when the FLA batteries die

The following colour legend is used while presenting the comments: Blue cells indicate a loss from the intervention, green cells indicate a gain, white cells are items for which a clear answer cannot be given.

Interventions at the Building level	Technical	Economical	Social	Environmental
Replace FLA batteries with VRLA, at end of life	Similar performance as before; higher lifetime can be expected	Economical as VRLA batteries have a longer lifetime than FLA batteries (6-7 years) and do not have maintenance cost, which makes lower cost per kWh delivered	No more maintenance needed; Safer type of battery (no gas emissions); can be installed anywhere since there is not too much heat	VRLA are not environment-friendly but last longer (on the long run better than FLA) Reduction of 7% of energy footprint Reduction of 12% of greenhouse gas emission
Replace FLA batteries with Li-ion, at end of life	Huge technical improvement as Li-ion has high discharge rate, lasts very long, performs well in hot climate, and more reliable	High setup costs and need to adapt the monitoring system; but Li-ion can be undersized due to the higher depth of discharge, longer life reducing the Rs/kWh cost	Maintenance free, no gas emissions, low self discharge rate, can withstand a partial state of charge, very flexible to unconscious use	Reduction of 33% of energy footprint Reduction of 27% of greenhouse gas emission Can be stored (non-toxic
Connect a grid interactive system to the house (with smaller battery backup) at end of life	Use of the system is maximized as surplus can go to another building if loads are not there; no downtime	Costs of connecting a community to the grid have been estimated to 1/3rd the cost of replacing all the batteries of this community during a 10-year period. Any surplus energy from the system can be exported to the Grid. Energy audits are needed to estimate the total energy that can be exported.	No downtime; possible to install energy intensive appliances. Green belters may resist this intervention as development is encouraged[6]	Batteries are environmentally harmful, and limiting the capacity installed reduces the adverse impact
Install centralized storage and sourcing by community… (common features)	Buildings cannot be too far from a central point. Losses in the lines could be minimized, e.g. having one central inverter and transmitting AC. If offices and houses are both connected, then the usage will be evenly spread over the day	Better financial returns than having one system per house, which ends up being over sized. Extra costs are caused by necessity of a new room	Could enhance perception of "community", as several houses use and maintain a single installation. In case of malfunction, several houses face a blackout. Maintenance is centralized. Using a remote monitoring system, people can be aware on how much energy is available in the bank.	Having one system is environmentally friendlier than having several small-scale systems (e.g. less transportation). Discarding several usable batteries poses an environmental hazard.

Interventions at Community level	Technical	Economical	Social	Environmental
...with a VRLA battery bank	VRLA has good lifetime, but is not flexible to deep DoD; if users deviate from the initial energy amount attributed, SOC will be low and battery's life much shortened	Better financial returns than FLA batteries (cheapest option).		Having such an amount of lead concentrated in the same spot is highly harmful for health.
...with a Li-ion battery bank	Huge technical improvement, due to high efficiency of the battery, long-life and flexibility to use	Better financial returns than FLA . But first investment is huge and adapted monitoring system has to be purchased. Great financial risk taken if any accident occurs	Li-ion allows shallow SOC + high discharge rate	Lithium does not present risks for human health. Lithium-ion batteries have very high number of cycles expected, which makes very high the ESOI and less the impact on environment
Connect a grid interactive system (with battery backup) at the community level when the FLA batteries die out	Use of the system is maximized as surplus can go to another building if loads are not there; but there will be losses in the line due to great distances between houses	Costs of connecting to the grid depend on the proximity of the LT pole and cannot be estimated accurately. Also, quantum of energy that can be fed into the grid could balance cost of energy imported and cost of installation.	No energy in case of a power cut, unless hybrid system is installed; possible to install energy intensive appliances. Green belters may resist this intervention as development is encouraged	Batteries are environmentally harmful, and limiting the capacity installed reduces the adverse impact

Table 3.13

[6]In case of overhead lines, it means clearing a corridor from trees and branches; creating such a corridor could result (unintentionally) in increased mobility. This is further elaborated in Part 3 of the SPV study.

Conclusion

Although Li-ion batteries are better than Lead Acid batteries in many respects, we are of the opinion that the high performance promised by Li-ion may not be required in Auroville, especially since Auroville buildings use small domestic loads that do not need a high rate of charge or discharge. If the reduction of environmental impact because of batteries is the only priority, replacing all types of lead-acid batteries to Li-ion batteries can be recommended. However, the sales and service network for Li-ion batteries is not yet well established in India.

As a result, we recommend that for now, FLA batteries in Auroville, and especially those that are being used in extensively in the Greenbelt, be upgraded to the VRLA type. A separate study to determine battery usage patterns in Auroville, and the kind of usage that provides the most savings on replacement can be undertaken.

In parallel, we recommend that a centralised storage system using Li-ion batteries be installed in a green belt community, as a pilot project, in order to verify the performance of Li-ion in a hot and humid climate, and validate the lower life cycle costs, efficiency and ease of use. Based on the results of the pilot study, more Li-ion installations in the Greenbelt can be planned. Since a majority of these are stand-alone systems, reduction on savings will be maximized. As photovoltaic and wind turbines become more affordable and widespread, the lightweight, long life cycle, and deep discharge capability of lithium-ion battery systems will enable a growing range of grid-connected, and off-grid products and applications to become economically feasible.

CHAPTER 4

Evaluating Solar Photovoltaic Systems in the Greenbelt

4

EVALUATING SOLAR PHOTOVOLTAIC SYSTEMS IN THE GREENBELT

Context

In this part of the study, we identify five communities in the Auroville Greenbelt that presently have no grid supply, with the objective of determining improvements to the existing Solar Photovoltaic systems (henceforth referred to as "SPV system". The first part of the report describes the current status of energy installations in these communities, using technical, economic, social and environmental parameters. Based on findings, different interventions are then considered for improving these systems in the Greenbelt.

The 5 Communities

The team identified 5 Greenbelt communities, in order to have a sample as representative as possible of the situation in the Greenbelt, with different building typologies.

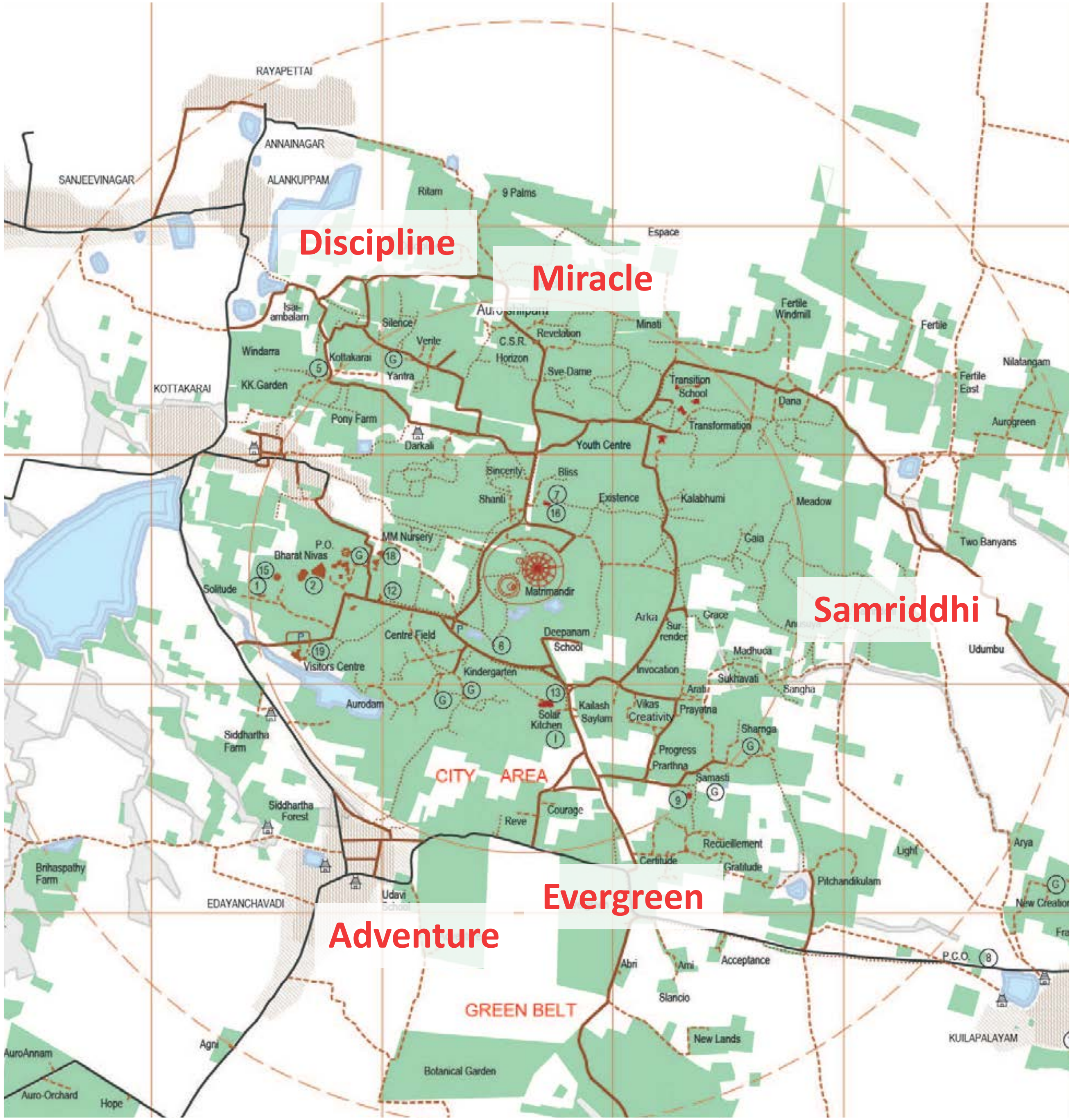
1. Adventure
2. Discipline
3. Evergreen
4. Miracle
5. Samriddhi

25 buildings (81%) are residences, 1 building is used as an office, and 2 as community kitchens. 3 buildings use a water pump in addition to the regular household load.

Community	kW
Adventure	7.57
Adventure community	0.30
Discipline	8.63
Discipline community	0.45
Evergreen	6.35
Evergreen kitchen	1.65
Miracle	2.00
Samriddhi	9.92
Grand Total	36.87

A total of 31 Solar Photovoltaic (henceforth, "SPV") installations were studied, using records from Sunlit Future and Solar Service (installers of SPV systems), email questionnaires & telephone interviews with the building stewards, as well as visits to each in these Communities. The questionnaire has been included as an Annex.

The total installed Kilowatt (kW) capacity in these communities is 36.87 kW as shown in the accompanying table.


Discipline
Miracle
Samriddhi
Evergreen
Adventure
RAYAPETTAI
ANNAINAGAR
ALANKUPPAM
SANJEEVINAGAR
KOTTAKARAI
EDAYANCHAVADI
KUILAPALAYAM
CITY AREA
GREEN BELT
Matrimandir
Visitors Centre
Botanical Garden

Technical parameters

This section analyses the selected SPV systems based on technical parameters, viz. age (as an indicator of reliability of the system), orientation of the panels and observations on health of the system.

Overview

All the energy systems in the sample communities are stand-alone off-grid SPV systems. They are equipped with solar panels, battery and inverter, except one that uses only DC loads and does not have an inverter. Two buildings use solar pumps in addition to the household loads. A majority of these (16 installations or 51%) have been installed by Sunlit over the past 7 years.

None of the buildings are connected to the grid, either for charging the batteries or for exporting surplus energy. All systems use a separate charge controller with a Pulsed Width Modulated (PWM) algorithm. Some houses use high voltage appliances such as refrigerators, and these residents have installed 2 SPV systems to power their loads.

The energy efficiency of system components is ideally calculated using meters (before and after the device), such as the AC kilowatt meter and a DC kilowatt meter (such as the Wattmon) on the DC side. Since this involves cutting and rewiring each installation, we have used age of the device to indicate balance lifetime expected from the device. However, in some installations, the year of manufacture for certain devices could not be determined, and an average value has been assumed for the calculations.

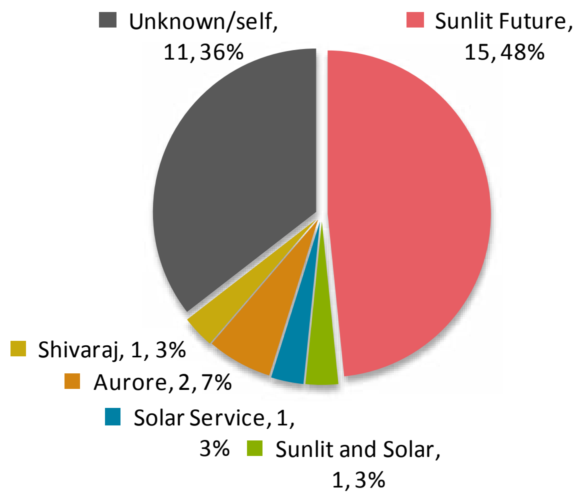


Figure 4.1: Installer of SPV system

Inverters

Majority of the inverters used in these buildings are offline Su-Kam inverters (15 of 31 inverters), followed by Sine-Wave (3 of 31), Kevin (2 of 31) and Base (2 of 31). 20 inverters (65%) are below 1.5kVA, 2 systems are 2 kVA and 2 are 3.5kVA. Also, the age of 19 inverters (61%) could not be determined, as neither the residents nor the installers had the necessary information.

None of the systems inspected are protected with DC surge protection, and only one system amongst the 31 installations had AC surge protection. Also, none of the systems have any form of lightening protection devices protecting the SPC installation.

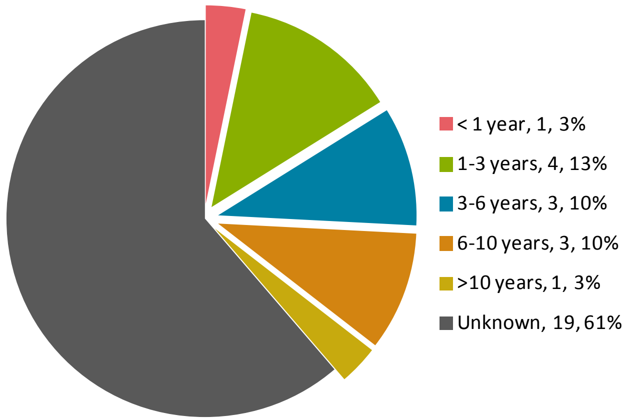


Figure 4.2: Age of inverters

Solar Photovoltaic Panels

Most Solar Photovoltaic Panels (SPV) panels are poly-crystalline technology, but mono-crystalline is also noticed in the newer installations. Panels are normally expected to last 20 years. However, the age of the panels in a majority of the installations (15 buildings) could not be determined, and of the remaining, panels in 13 buildings are below 10 years of age. At times, more than one type of SPV panels have been used, and frequently residents have installed second hand panels.

Majority of the systems in the sample communities were less than 1kW (18 buildings or 58%). 7 systems are between 1-2kW, and the remaining 6 buildings had a total capacity of greater than 2kW. The capacity installed per person in each of these buildings will be explored later in the Paper.

Installation: In the northern hemisphere, panels are ideally installed facing South, and tilted at the same angle as the latitude of the location. Auroville is located at ~12°N latitude and hence, the optimum angle of the panels is 12°. Alternatively the panels can be installed in the East-West direction along with a tracker that tracks the movement of the Sun, and tilts the panels accordingly. In the absence of the tracking device, efficiency of the panels can be maximised if they are installed at a tilt of 12° facing South.

In the sample communities, only half of the panels have been installed using this approach. It appears that panels have been installed using other criteria such as the slope of the roof, availability of space, a need to hide the panels from line of sight, etc. Three installations have panels inclined at ~30° reducing efficiency by 6%, and in three other setups, the panels are inclined at 45°, leading to a 14% loss in efficiency (www.energie-developpement.blogspot.in)

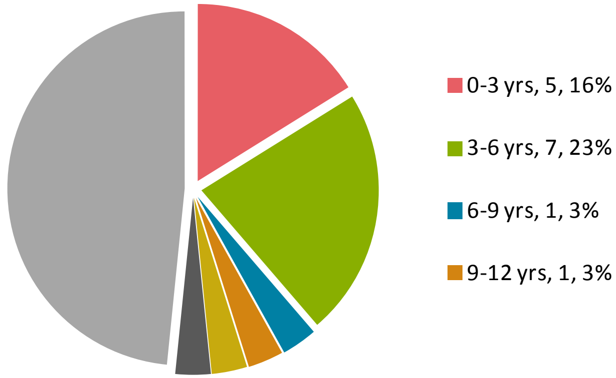


Figure 4.3: Age of panels

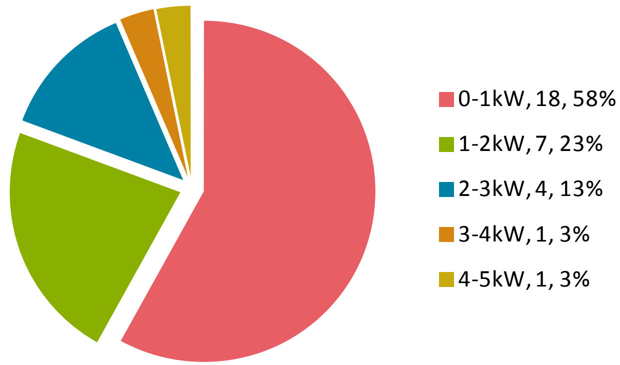


Figure 4.4: Total panel wattage

6 buildings have tracking devices; but in least 3 of them, the tracker is not in a working condition. The tracker can still be moved manually, but the residents do not change the tilt, and hence, the panels end up in the same position all day.

No layout drawings are available for any installation, making it challenging to propose technical interventions.

Also, of the 30 installations that we visited:

- Residents in 5 buildings (16%) reported that panels are not being cleaned and maintained on a regular basis
- Either the panels or the SPV system is not easily accessible in 14 installations (46%)
- 12 installations (40%) have dust and dirt on the panels.

Mounting: Panels are roof mounted in 16 installations (60%), and in a majority of the installations, the structure is strong, and does not shake or tremble when force is applied; bolts, nuts, fasteners and clamps are in good condition in almost all the cases where the panels were accessible. Also, no seepage or dripping of water from the sides of the panel or from the groove holes was noticed during time of inspection. The SPV mounting seems to be reliable over the lifetime of the panels.

Item	Value	Number
Orientation	North-South	20 (67%)
	East-West	5 (17%)
Angle	~6°	5 (17%)
	~12°	15 (50%)
	~30°	3 (10%)
	~45°	3 (10%)

Table 4.1

However, many panels have been roof mounted, without a convenient way to access the panels for cleaning and maintenance. Ground mounted installations tend to have more dust and dirt on them, especially in the Green Belt. Also, there are higher chances of shade from the trees falling on the panels. Natural and/or man-made shading was observed on the panels in 6 installations (20%). Any amount of shading on the panels, affects the quantum of energy they can produce.

Batteries

Overall, the batteries appear to be well maintained. Neither cracks nor fluid around the batteries were observed, indicating good health and reliability. In 45% of the cases, there is space for increasing the storage capacity, and in 90% of the cases there is space around the battery to install few additional batteries if the need so arises.

There is no clear-cut method of determining the number of cycles a battery has completed (or the number of charge cycles a battery can still deliver). Condition of two batteries (and the balance life) could be determined by measuring voltage and specific gravity. However, as batteries are not always used in deep cycles, it is difficult to ensure that the battery is fully charged (or fully discharged) when measuring voltage. Also a hydrometer can be used to measure specific gravity, but this will not work on VRLA batteries since they are sealed. Health of the battery could also be measured in determining power delivered by the battery in one full discharge cycle or one full charge cycle. However, each of these measures shortens the battery life.

As a result, for the purposes of this study, we considered the age of the batteries as an indicator of their efficiency. Given the type of use in Auroville, Rama (of Solar Service) recommends changing FLA batteries every 3-4 years. Sunlit Future have been installing VRLA batteries from Amara Raja, and these are generally lasting 6 years. Lithium-ion batteries have not yet been installed in Auroville. However, given that they are less sensitive to usage factors (such as state of charge during use, excessive charging or discharging, climate, etc.), we assume that they would last at least 10 years (as guaranteed by the manufacturer). The table below provides a quick glance of the type and age of batteries in the sample communities.

Battery Type	< 1 year	1-3 years	3-6 years	6-10 years	Unknown age	Total
Lead Acid, FLA	2	4	5	1	17	29
Lead Acid (VRLA)		2			1	3
Lithium Ion (Li-ion)						0
Total	2	6	5	1	18	32

Table 4.2

Efficiency of a battery decreases (approximately) linearly when age increases. This is due to a build-up of internal resistance, increase of impedance and loss of conductance. In FLA batteries, Sulfation reduces the overall capacity of the battery (see Part 2 of the study for further details). Also, many residents in the sample communities have not been applying a top up charge to their batteries during idle time, which could have affected the health of the batteries. Also, only 3 systems are equipped with Valve Regulated Lead Acid (VRLA) batteries; these last much longer than Flooded Lead Acid batteries (FLA) batteries (twice as long on average), and therefore, they are more efficient over the same lifespan. Some guidelines for extending the lifetime of a battery are provided in the Annex.

Economical parameters

When efficiency cannot be measured, age is the most reliable indicator of the current efficiency of a component. Observations have shown that efficiency of batteries has not been maximized due to lack of maintenance as detailed out in the previous section. The following section aims to quantify the current economic value of the installations in the sample communities.

Neither the installers, nor the residents have maintained original bills of many of the systems. As a result, we have taken averages, and retro-priced each device, in order to estimate the cost of the initial investment, depreciation, cost of maintenance, resale value and cost of replacement. The following table lists the assumptions and values for these calculations:

Device	Item	Value	Source
Social	Total no. of people	54	Survey
Panel	Total no. of panels	383	Field visits
	Average age of panels	5 years	Residents of buildings, Sunlit
	Total wattage	7,632W	Calculated field
	Avg. price per watt of a panel	Rs. 50	Source: Part 1/Sunlit Future
	Price per Watt in 2008	Rs. 80	Source: Sunlit Future
	Average resale value	Rs. 100	Source: EcoService/AuroScrap
	Depreciation per year	80%	Prabhasari Accounting
Inverter	No. of inverters	30	Considering one per installation
	Average age	4.5 yrs.	Residents of buildings, Sunlit
	Total summed capacity of inverters	32 kVA	Calculated field
	Price per kVA	Rs. 6,786	Source: Sunlit Future
	Price per kVA in 2010	Rs. 6,786	Source: Sunlit Future
	Average resale value	Rs. 2750	Source: EcoService/AuroScrap
	Depreciation per year	25%	Prabhasari Accounting

Table 4.3

Cont...

Device	Item	Value	Source
Battery	Total no. of batteries in the system	81	Field visits
	Average age	3 years	Residents of buildings, Sunlit
	Total summed capacity of storage	199 kWh	Calculated field
	Cost of maintenance per month	Rs. 50	Source: Sunlit Future/Solar
	Cost for FLA, per Wh in 2014	Rs. 8.5	Source: Solar Service
	Cost of FLA per Wh in 2011	Rs. 11.05	Source: Sunlit Future
	Average resale value	Rs. 1,500	Source: EcoService/AuroScrap
	Cost per Wh of VRLA	Rs. 10	Source: Sunlit Future
	Cost per Wh of Li-ion	Rs. 49	Source: Sunlit Future
	Depreciation per year	25%	Prabhasari Accounting
No. of Charge Control-lers	30	Field visits	
	Average age	4 years	Residents of buildings, Sunlit
	Average price	Rs. 6,000	Source: Sunlit Future
	Price in 2010	Rs. 6,000	Source: Sunlit Future
	Depreciation per year	25%	Prabhasari Accounting

Table 4.4

Cont...

Based on the above, an approximate cost of initial investment and current book value is given below.

Item	Panels	Inverters	Batteries	Charge con-trollers	Total
Average cost of sys-tems (INR)	6,10,560	2,17,482	21,98,950	1,80,000	32,06,992
Percentage of total cost	19%	7%	69%	6%	100%
Depreciation %	80%	25%	25%	25%	N.A.
Avg. current value after dep.	195	59,594	9,27,682	56,953	10,44,424

Table 4.5

Replacement cost

If all system components in the 5 communities were to be replaced in one go at current market prices, then the total investment cost will be Rs. 25 lakhs (given in the table below). Scrapping or reselling the current devices can help reduce costs. Resale prices of system components depend on their age and working condition. Copper and wire in the inverters and charge controllers are valuable if in working condition. Panels cannot be recycled, but the glass is valuable; average resale value is Rs.100 per panel. If all devices and system components in the sample communities are scrapped, then the net investment cost drops to Rs. 22 lakhs, or Rs. 40,000 per head in these communities.

Component	Replacement cost (INR)	Resale value (INR)	Net cost (INR)
SPV Panels	3,81,600	38,300	3,43,300
Inverters	2,17,482	82,500	1,34,982
Battery	16,91,500	1,21,500	15,70,000
Charge controller	1,80,000	45,000	1,35,000
Total	24,70,582	2,87,300	21,83,282

Table 4.6

Social parameters

This section will analyse the installations in the 5 sample communities based on social parameters. This includes the size of the system in relation to the size of the household, security aspects, whether the installed system is satisfying energy needs, as well as the opinions of the building stewards regarding connecting to the grid and community-centralized systems.

Overview

Out of 31 installations, 28 of them are houses with 3 of them equipped with pumps, 2 are community kitchen and 1 is an office. Households are mostly of small size. Most buildings are not equipped with monitoring systems such as the Wattmon, and the building stewards do not have an objective way of determining their load consumption and state of charge of their batteries. Also, only one person mentioned having a solar charge current sensor.

Size of the system

We estimate the total energy produced by the SPV installation using the following formula

E = P x 24 x 365 x CUF

Where

- E = energy generation per annum in kWh
- P = power of the system, viz. number of panels x wattage

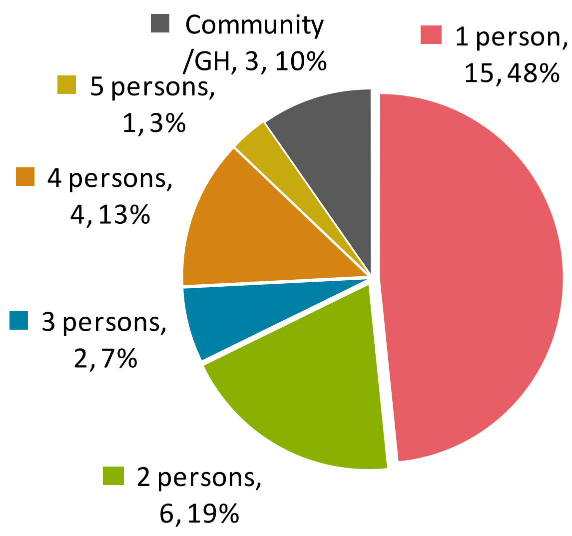


Figure 4.5: No. of persons per household

- CUF or Capacity Utilisation Factor = coefficient of efficiency of the system, taking into account the efficiency of the panels and inverter and hours of sunshine. Considering the use of second hand panels and the age of the panels we have considered CUS as 15% (rather than 18%) for the purposes of this study.

Based on the above, we calculate the total energy production in the 5 communities as approximately 47,000 kWh per annum. The distribution of these 47k units is shown in the following table.

Community	Persons	Installed kW	Systems	kWh/annum	kWh / person / annum
Adventure	14	7.57	8	9,947	710
Adventure shared system	Unclear	0.30	1	394	
Discipline	11	8.63	7	11,341	1,031
Discipline shared system	Unclear	0.45	1	591	
Evergreen	10	6.35	3	7,358	736
Evergreen shared system	Unclear	1.65	1	2,168	
Miracle	8	2.00	2	2,628	329
Samriddhi	11	9.92	8	13,033	1,185
Grand Total	54	36.87	31	47,461	879

Table 4.7

Correlating the above with the number of residents in each building, we do not find a relation between:

- Size of the system and number of residents
- Battery capacity and number of residents
- Inverter size (kVA) and number of residents

This is illustrated in the accompanying three graphs. The lack of correlation between any of these parameters indicates that the lifestyle of residents varies widely, and system size and capacity is not related to the number of persons using the system.

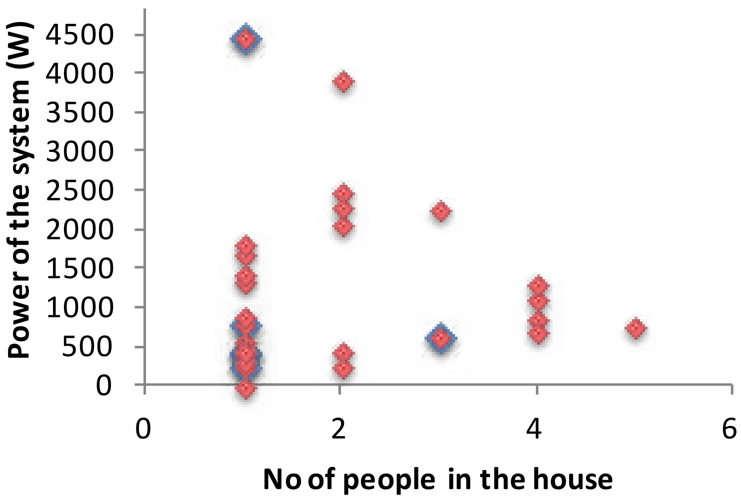


Figure 4.6

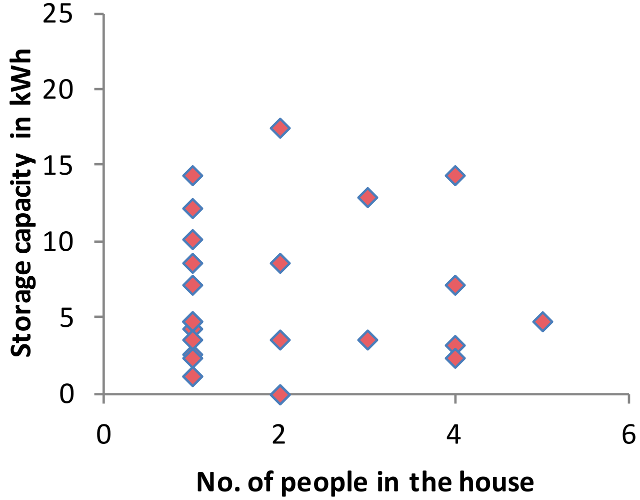


Figure 4.7

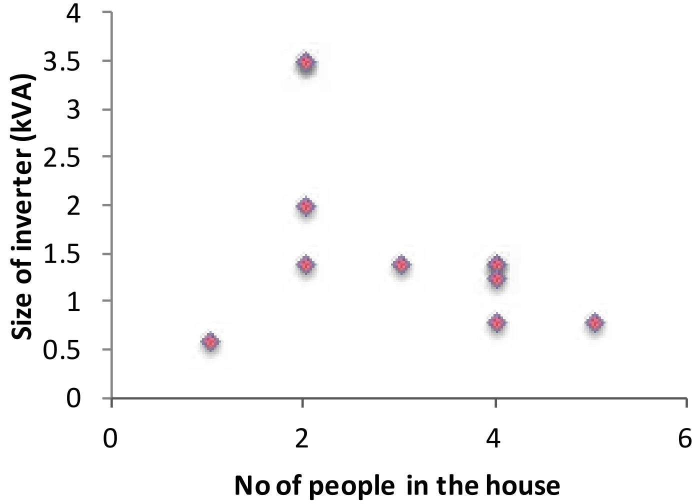


Figure 4.8

Satisfaction and feelings

Residents of the 5 communities were interviewed to understand their perspectives of interventions that could be considered for improving the SPV systems. The following questions were used to initiate a discussion:

1. Is the current SPV system sufficient for your needs?
2. Are you open and/or interested in connecting your SPV system to the grid?
3. What is your feeling about centralizing/sharing the production and storage of energy at the community scale?

Sufficiency:

Residents of 12 buildings have mentioned that their systems are not fulfilling their present energy needs; power blackouts are frequently encountered (especially during cloudy days). Residents mentioned that they believe this is because “the panels are too old”, or the “batteries are not charging anymore”. While this may be true, we believe that the factors mentioned previously (dirt and dust on the panels, inaccessibility of the panels for cleaning, shade on the panels, incorrect angle and direction of installation, insufficient battery maintenance, inappropriate load distribution, etc.) have contributed to energy losses that could have been avoided. Energy audits in these buildings can help to identify the actual cause, and ways to conserve energy and increase efficiency.

6 residents expressed the need to expand their system because it doesn’t support certain appliances. 2 residents mentioned that their guests are drawing energy for which the system had not been sized. 4 mentioned that their panels are old but in working condition, though they face blackouts at night time each day. However, they have not replaced them since they are in working condition.

Connecting to the grid:

We asked the residents if they would be open to convert their systems to grid-connected Solar PV systems, giving them the opportunity to import energy from the grid (on cloudy days or at night for instance), and export any surplus energy to the grid. Responses are categorised as “against”, “undecided” & “favourable”.

7 residents (32%) are “against” the idea of grid connectivity in their communities. The reasons cited were as follows:

- “It would disturb the forest, that would make too many trees to cut”
- “Overhead lines are wasting acres of land already”
- “Underground lines will make path/roads for maintenance, we do not want roads”
- “It will make more people to come to the forest if there is electricity”
- “Using electricity coming from power plants is as bad as using batteries”
- “People should adapt their needs, and

not the opposite"
- "People will start to live the same way as in the centre"
- "People won't care anymore for what the energy they use"

8 residents (36%) people were "undecided" in having TNEB in their communities. Reasons cited were as follows:
- "Our needs are met with solar and we do not see the point"
- "It is contradictory with the policy of the Forest group but would be open to it, if it makes more sense environmentally"
- "We are happy without electricity from the grid"
- "We were told by the people from the Forest Group that it is not the policy and that it is absolutely out of question in the Greenbelt"
- "People around are generally against this idea"

7 residents (32%) are "favourable" to connecting to the grid, even though they were initially opposed to the idea, as the Forest Group does not allow it.
- 2 residents emphasized the fact that TNEB is only 50m or 100m far from their house, and in one case, the community is already surrounded regions with electricity
- 1 resident already has the system ready to connect to the grid, but is lacking the necessary permissions
- 1 resident would connect the storeroom to the grid but not the house
- 1 resident emphasized that connecting to the grid would be "a relief from a nightmare" of trying to understand all the technical details involved in a SPV system
- 1 resident would like to have the grid so that excess energy can be exported

Shared storage system:

We asked the residents if they would be open to having a shared storage system in their communities, that the residents could draw from. This would lead to economies of scale as detailed in our previous study. Responses have been categorised as "firmly opposed", "slightly against" & "in favour".

6 residents (27%) people were "against" the idea of a shared storage system for their communities. Reasons cited were as follows:
- "People are correctly managing with individual systems and installing a shared one would only lead to conflicts"
- "People like it individual", "finding an agreement would be a headache", "more the people, more the fights"
- "In case you are independent, you penal-

ize only yourself if you take too much" "People won't care for being conscious with a shared system"
- "It is "a total non-sense" in terms of efficiency and social management"
- "The community is spread in too big an area, this should be tried in a denser neighbourhood"

6 residents (27%) were "undecided" on the idea, at least for their community, because:
- "There is a problem of responsibility: who will take the burden of checking each person's consumption?"
- "How to distribute the costs if consumptions are not equal? People shouldn't be deprived of the comfort they need"
- "Who will switch the inverter in case of lightening?"
- "Individual systems work very well, and better than centralized systems, unless one meter per house is controlling everyone's consumptions"
- "People won't want to see the systems they invested in to be pulled together, but it should be tried in a new place with no systems yet, as an experiment, and then maybe being extrapolated"
- "The next neighbour is 800m far so it doesn't make sense to make energy travel such distance (would be favourable if someone settles closer)"
- "Guesthouse and residencies cannot share the same system"

10 residents (45%) are "in favour" of a shared storage system at the community scale:
- "It can lead to conflicts but I would definitely go for a trial"
- "It would take all my troubles (of maintaining the system) go away"
- "It is the ideal combination: it is in the spirit of the Greenbelt AND in the spirit of Auroville!!"
- One resident is open to the idea of centralizing at the scale of Auroville itself
- One person asked if the efficiency of such centralization could be first demonstrated; if it is, then definitely favourable
- One person already does it and would name a responsible person for switching off the inverter

Discipline community has already considered the idea of centralizing the SPV system. They have made a rough calculation of the costs of connecting the community to the grid (energy needed for the pumps) and investing in a large system. Houses will need to be provided with a single-phase connection, and 3-phase for the pumps. Costs are found to be very high due to the distance of each building from one another. The community concluded that they could not afford it, and they abandoned the idea. However, according to one resident, if funds can be raised, then Discipline community would be ready to shift to a shared system.

Monitoring

No data logging, automation and monitoring system (such as the Wattmon) was observed in any building. Some residents claimed to be conscious of what they draw from their systems. However, since residents have been experiencing blackouts, it shows that residents are not well aware of the energy produced and the consumption load patterns.

Space and Security

Cabling, wiring, and protection devices in the sample communities were surveyed by site visits. In 25 buildings (83%), wiring does not pass through PVC conduit pipes. In 20 buildings (65%), wiring is not secured by staples, cable ties or straps, and is found to be loose. In 24 buildings (77%) wires are exposed and are not secure or nicely tied. None of the installations had AC or DC surge protection devices, as well as lightening protection devices, leaving much scope for improvement. Lead acid batteries of flooded type emit gasses; to prevent accumulation, the batteries should be stored in properly ventilated space. However, 9 buildings (29%) do not have proper ventilation.

Conclusion

Data shows that buildings in the sample communities have widespread needs, and varying size of systems, from 1.5 panels per person to 30 panels per person. Lifestyle varies, and some residents have dual systems to power their loads. The option of connecting to the grid seems to varying reactions from the residents, as well as the idea of centralized storage. Lack of safety is noticed in many installations and could be improved quality of solar installations.

Environmental parameters

The following section analyses the systems in the Greenbelt based on environmental parameters, viz.

Eco-friendly lifestyle

In the Greenbelt, people mostly claimed to have adapted their needs to the system. The dominating trend is to use appliances in function of the power supply instead of expanding the system each time a new appliance is needed. Most residents could be called 100% prosumers since they use only what they produce, and the net energy balance is nil. Once the system is installed and commences operations, it does not have an impact on environment. Also, 3 buildings use second-hand panels. Although this is not the most efficient, from an environmental perspective, using a material until its end of life is ecological.

Embodied energy

As discussed in Part 1 of the study, a stand-alone SPV system has an embodied energy of 0.294 kWh per kWh. The related CO_2 emission equivalent is 0.449 $kgCO_2e$ per kWh consumed. The table below presents the energy and CO_2 footprint in each of the five sample communities.

Community	kWh produced per annum	Energy footprint per annum (kWh)	CO2 footprint per annum (kgCO2e)
Adventure	9,947	2,924	4,466
Adventure shared system	394	116	177
Discipline	11,341	3,334	5,092
Discipline shared system	591	174	265
Evergreen	7,358	2,163	3,304
Evergreen shared system	2,168	637	973
Miracle	2,628	773	1,180
Samriddhi	13,033	3,832	5,852
Grand Total	47,461	13,954	21,310

Table 4.8

Land requirement

Stand-alone SPV systems as well as grid connected SPV systems have a land footprint. One kilowatt of Solar PV panels requires 12m2 of space. In the sample communities, panels in 7 buildings (approximately 8kW) are ground mounted; indicating that 96m2 of ground space has been utilized.

If systems are connected to the grid using overhead lines, then 3 meters on either side of the line (a total 6mts.) must be cleared for servicing and maintenance. In the case of underground cables, a trench of 2mts width is required to lay the cables. Hence, the land requirement is as follows:

Community	Distance to nearest LT Pole	Current Land Footprint (ground and roof)	Land footprint (for over head cabling)	Land footprint (for underground cabling)
Adventure	278 mts.	94 m2	1,668 m2	556 m2
Discipline	206 mts.	109 m2	1,236 m2	412 m2
Evergreen	187 mts.	96 m2	1,122 m2	374 m2
Miracle	126 mts.	24 m2	756 m2	252 m2
Samriddhi	445 mts.	119 m2	2,670 m2	890 m2
Total		442m2	7,452 m2	2,484 m2

Table 4.9

Recommendations

Based on the previous sections we have identified the following general interventions in the five sample communities.

1. Install monitoring and evaluation systems
2. Sponsor maintenance of systems
3. Strengthen the Solar Fund
4. Replace the Flooded Lead Acid (FLA) batteries
5. Expand system capacity
6. Convert to grid-interactive SPV systems
7. Install a Centralized system of sourcing and storage

Install a monitoring and evaluation system

The first improvement that can be made is to provide a monitoring and evaluation system per installation. Wattmon is a stand-alone energy monitoring and control device that can track battery bank capacity and generate reports on energy produced and consumed. It can be programmed to take specific actions automatically, and can be accessed remotely. Wattmon can also be used in water tanks to automate the pumping based on water level as well as optimise battery charge and discharge.

The 5 sample communities entail an investment of around INR 4 lakhs (for 31 Wattmon devices). This will enable each household to check if their systems are performing as per expectations, optimise loads as per stored capacity, and avoid blackouts.

Sponsor maintenance of systems

Overall, there is scope for improving the maintenance of the SPV systems. Some people reported that solar setups are “a nightmare”, as they are unable to understand how it works and why it “sometimes breaks down without any apparent reason”. Dust, dirt, shade on the panels cause energy losses up to 30%. Another resident mentioned loss of batteries due to negligence in maintenance. A top-up charge is not being provided to the batteries. Monthly topping-up helps eliminate Sulfation and to extend battery lifetime.
Panels in 7 buildings (23%) are not accessible for cleaning and maintenance. Either changing the location of such panels, and/or ensuring ease of access to the panels will assist in maximizing the energy produced with the existing systems.

A team of qualified technicians would thus be a worthwhile investment to provide technical support for use and maintenance of the SPV systems. This will help maintain the existing systems and increase their efficiency (and reduce the number and duration of blackouts), before installing additional panels and batteries. Some guidelines for maintaining panels is provided in the Annex.

Strengthen the Solar Fund

During the course of the telephone interviews, residents expressed the following:

- 7 residents (32%) wish to have financial support for replacing components such as batteries, charge controllers and inverters when these components reach their end of life
- 3 residents (14%) mentioned that they wish to upgrade / replace system components right away, but they cannot afford to do so.
- 1 resident mentioned that the Solar Fund provides assistance on first-come-first-served basis, and it does not evaluate the needs of the resident for disbursing funds. This person also mentioned that there is not enough funds available for maintaining (let alone upgrading) the SPV systems in the Greenbelt.

Based on the above, we find the need for the following measures:

- Provide guidelines regarding quality and price on SPV components
- Create policies and guidelines for the disbursement of (solar) funds
- Initiate a Purchasing Service that assists residents in procuring SPV components
- Audit the disbursement of funds by checking on quality and workmanship of the installation

Replace the Flooded Lead Acid (FLA) batteries

As per Part 2 of this study, we have recommended that all Flooded Lead Acid (FLA) batteries be replaced with Valve Regulated Lead Acid (VRLA) batteries. Benefits of VRLA batteries are given below:

- VRLA batteries have been found to be technically, socially, economically and environmentally superior to FLA batteries
- VRLA batteries do not emit gas that can inflame and therefore do not need to be stored away from electrics in a ventilated room
- VRLA batteries are sealed, and there is no risk of leakage or acid pouring out
- They do not need to be filled with distilled water
- They have a longer length of life (6-7 years instead of 3-4 years)

The reduction in the annual energy footprint by replacing Flooded Lead Acid Batteries with either the Valve regulated Lead Acid batteries or Lithium-ion Batteries is given in the table below.

Community	Replacing FLA with VRLA (kWh per annum)	FLA with Li-ion (kWh per annum)
Adventure	207	930
Adventure shared system	8	37
Discipline	236	1,060
Discipline shared system	12	55
Evergreen	153	688
Evergreen shared system	45	203
Miracle	55	246
Samriddhi	271	1,219
Grand Total	987	4,438

Table 4.10

The cost of replacing all the FLA batteries in the sample communities is given below.

Intervention	Approximate Cost
Replace existing FLA batteries with new FLA batteries (not recommended, but provided for comparison purpose only)	Rs. 16 lakhs
Replace existing FLA batteries with VRLA batteries	Rs. 19 lakhs
Replace existing FLA batteries with Li-ion batteries	Rs. 96 lakhs

Table 4.11

Although Li-ion batteries are better than Lead Acid batteries in many respects, we are of the opinion that the high performance promised by Li-ion may not be required in Auroville, especially since Auroville buildings use small domestic loads that do not need a high rate of charge or discharge. Also, the sales and service network for Li-ion batteries are not yet well established in India. As a result, we recommend that for now, all FLA batteries in Auroville, and especially so in the Greenbelt, be upgraded to the VRLA type. In parallel, we recommend that a centralised storage system using Li-ion batteries be installed in a selected Greenbelt community, in order to verify the pros and cons of Li-ion in a hot and humid climate, and confirm the lower life cycle costs, efficiency and ease of use.

Expand system capacity

Energy audits are needed to determine specific measures for each household. In some cases, a switch to 5-star rated appliances can help prevent blackouts without changing the SPV systems, while in other cases, the building may require the panel(s), batteries and other system components to be increased/replaced. Load could be substantially reduced, thereby reducing the need for additional capacity, and stress on the existing systems. The health of the panels and batteries also need to be checked. Without a better understanding of the loads and systems in each building, it becomes difficult to recommend specific improvements to the existing setups. However, broad figures for the sample communities are provided below:

Intervention	Approximate Cost
Increase battery capacity to 150% with FLA batteries (not recommended, but provided for comparison purpose only)	INR 24 lakhs
Increase battery capacity to 150% with VRLA batteries	INR 29 lakhs
Upgrade all charge controllers to 48V, 60A	INR 3 lakhs
Add 2 panels of 140W each per installation	INR 5 lakhs

Table 4.12

Note: The above interventions cannot be undertaken in isolation. Each SPV system needs to be studied, in order to ensure that it can accommodate the increased capacity.

Convert to grid-interactive SPV systems

All systems in the sample communities are presently off-grid stand-alone SPV systems. Ideally, these require a battery backup system that can power the full load. In grid interactive systems, energy is generated during the day, which is utilized by the building load, and the excess energy is fed into the grid. Where solar energy is not sufficient, then the consumption loads are powered by drawing from the grid. These systems work on net metering basis with the resident paying the Utility for the net energy imported from the grid. In case the grid fails, then the SPV system cannot be utilized. The following table lists the pros and cons of grid-interactive systems.

Parameter	Technical	Economic	Social	Environmental
Pros	No more loss of energy due to battery inefficiency and self-discharge, as daytime loads can be powered directly by the grid bypassing the batteries	Removing batteries from the setup incurs financial savings; indirect income from the export of surplus energy	Availability of energy increases, as energy can imported on cloudy days and night-time; wider range of domestic appliances, such as washing machines, refrigerators and air conditioners cannot be used	Batteries are not necessary anymore, and removing them from the setup provides environmental benefits.
Cons	Grid is not stable, lack of energy during a power cut; UPS and battery back up needed for essential loads during power cuts.	Residents may install additional appliances that were previously not feasible, and net overall energy consumption may increase.	Presence of grid encourages development in the area, which may lead to increased encroachment on Auroville land. Resistance from residents and from different working groups is likely.	Consumptions is likely to increase, resulting in increased carbon emissions. Loss of habitat, as grid interactive systems has a larger land footprint.

Table 4.13

Ideally, grid interactive SPV systems do not require battery back up as the grid acts as the backup for feeding excess solar power and vice versa. However, if there is a power cut, then essential loads cannot be powered, and to enhance the performance reliability of the overall systems, a minimum battery backup is recommended. A shared storage system can be considered for each community.

Community	kWh produced per annum	Annual CO2 emission produced by stand-alone system (kgCO2e)	Annual CO2 emission if produced by grid (kgCO2e)	Annual CO2 emission if produced by grid-connected system (kgCO2e)
Adventure	9,947	4,466	10,365	1,840
Adventure shared system	394	177	411	73
Discipline	11,341	5,092	11,817	2,098
Discipline shared system	591	265	616	109
Evergreen	7,358	3,304	7,667	1,361
Evergreen shared system	2,168	973	2,259	401
Miracle	2,628	1,180	2,738	486
Samriddhi	13,033	5,852	13,580	2,411
Grand Total	47,461	21,310	49,454	8,780

Table 4.14

These figures indicate that if the sample communities are connected to the grid, an equivalent of 2.64 kg of CO2 emissions would be saved per kWh produced. It should also be noted that these figures are calculated in case the system exports only 5% of the total produced; emissions would be less if more is exported. Hence, converting stand-alone systems into grid-connected systems has a positive impact on the environment.

Costs of installing grid interactive SPV systems in the sample communities are given in the table below. It is assumed that each building will be audited, and will be equipped with a grid interactive inverter, a Wattmon device for monitoring and evaluation, a bi directional kilowatt meter, and batteries replaced with VRLA batteries. The old inverters and batteries can be scrapped. The total amounts to Rs. 55 lakhs for the 5 sample communities. All costs are approximate, and a more detailed estimate needs to be prepared by the different Units that will be involved in this exercise.

Item	Adventure	Discipline	Evergreen	Miracle	Samriddhi
Number of SPV systems	9	8	4	2	8
Number of batteries	17	28	15	6	15
Current battery capacity (kWh)	47	42	51	10	49
Average distance to nearest LT Pole (m)	278	206	-	126	-
Average distance to nearest transformer (m)	598	238	194	220	704
No of LT pole to be added (roundup)	10	7	-	5	-
Cost of additionnal LT poles	100,000	70,000	-	50,000	-
Cable 16 square per meter	30,580	22,660	-	13,860	-
Trench, Kadapa cabling per meter	83,400	61,800	-	37,800	-

Table 4.15

Item	Adventure	Discipline	Evergreen	Miracle	Samriddhi
On-grid Inverters (Rs.51300 per Delta inverter)	461,700	410,400	205,200	102,600	410,400
Resale of old inverters (INR 2000 per inverter)	(18,000)	(16,000)	(8,000)	(4,000)	(16,000)
Wattmon (INR 13000 per system)	117,000	104,000	52,000	26,000	104,000
New VRLA batteries (INR 10 per Wh)	474,000	417,600	510,000	96,000	492,000
Resale of old batteries (INR 1500 per battery)	(25,500)	(42,000)	(22,500)	(9,000)	(22,500)
Box, switch, fuse, etc. (INR 22000 per building)	198,000	176,000	88,000	44,000	176,000
TNEB charges (INR 8000 per connection)	72,000	64,000	32,000	16,000	64,000
Electrical labour charges (INR 2000 per system)	18,000	16,000	8,000	4,000	16,000
SPV installer charges (INR 5000 per system)	45,000	40,000	20,000	10,000	40,000
Energy audits for load optimization (INR 5000)	45,000	40,000	20,000	10,000	40,000
Miscellaneous charges (transport, overtime, etc.)	27,000	24,000	12,000	6,000	24,000
Total for aerial cabling	1,544,780	1,326,660	916,700	365,460	1,327,900
Total for underground cabling	1,497,600	1,295,800	916,700	339,400	1,327,900

Centralized system of sourcing and storage

As concluded in Part 2, the efficiency and performance of Lithium-ion batteries in a hot and humid climate needs to be verified. If the lifespan exceeds 2 times the lifespan of current VRLA batteries, Lithium-ion will even become economically competitive .

Given the technical features of Li-ion batteries (viz. charge and discharge rates, deep depths of discharge), the pilot Lithium-ion system could be designed as a shared system of sourcing and storage for a given community. A cost estimate for Discipline Farm is given below.

Assumptions	Value
Total battery storage capacity of Discipline Farm (kWh)	56
Average size of inverter (kVA)	1.28
No. of buildings considered	8
Total no. of batteries	31
Total no. of inverters	8
Total no. of charge controllers	8
Average value per battery if scrapped right away (INR)	2,750
Average value per inverter if scrapped right away (INR)	2,750
Average value per charge controller if scrapped right away (INR)	2,750
Approx. price per Wh of Li-ion batteries (INR)	49.0

Table 4.16

Calculation	
Price for Li-ion centralized battery incl. BMS (INR)	2,751,840
Cabling for triple phase (underground)	61,388
On-grid inverters	410,400
Box, switch, fuse, etc (Rs.22000 per system):	176,000
TNEB charges (Rs.8000 per connection):	64,000
SPV installer charges (Rs.5000 per system):	40,000
Miscellaneous charges (transport, overtime, etc):	24,000

Table 4.17

Assumptions	Value
AVES charges (10% of the bill)	77,579
GRAND TOTAL TRIPLE PHASE	853,367
Resale value of batteries if scrapped (INR)	(85,250)
Resale value of charge controllers if scrapped (INR)	(22,000)
Net cost of installing centralized Li-ion storage in Discipline (INR)	3,497,957

Table 4.18

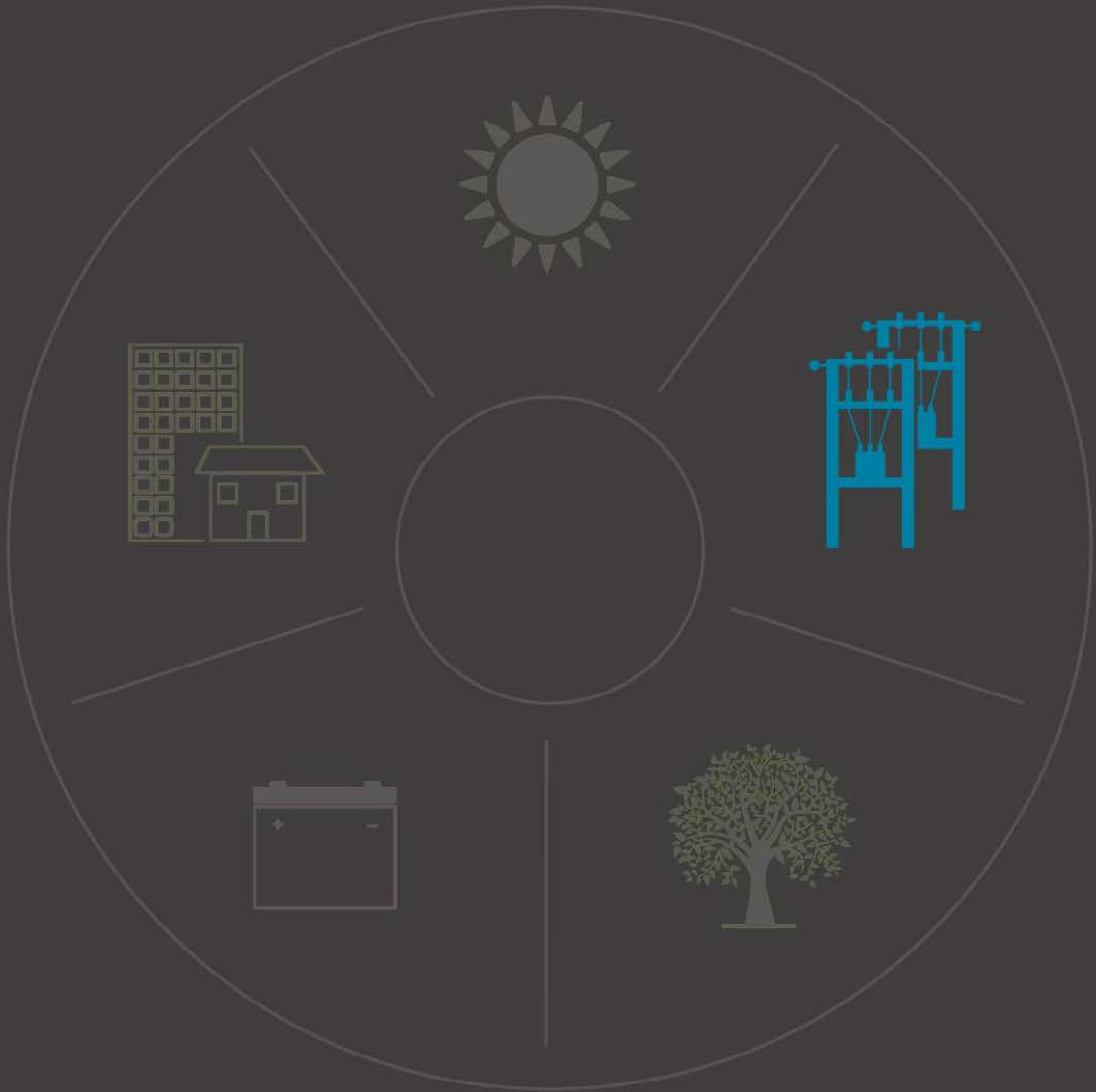
Conclusion

While stand-alone SPV systems in the Greenbelt initially started out with the best intentions, they are currently lagging behind in terms of maintenance and efficiency. The fact that some residents are experiencing blackouts calls for immediate action to provide assistance in any manner possible. This includes finances as well as technical knowhow and guidance. Many residents are at a loss to understand the different SPV components and methods to use and maintain them. The move to connect a community to the grid should be re-discussed with the relevant working groups in Auroville (L'Avenir/ TDC, Forest Group, Residents Service, Working Committee, etc.) A pilot grid interactive SPV system can be installed in a single community before proceeding with the other communities. Installation of a centralized storage system can be proposed only to communities where the majority are in favour.

The presence of numerous units operating in the field of energy (commercial units such as Auroville Energy Products, Auroville Consulting and Sunlit Future; Working Groups such as the TDC and the Solar Fund; Services such as AVES and Solar Service, as well as outside companies from Pondicherry actively seeing the Auroville market) seems to have created a confusion amongst the residents regarding who to approach for which issue. We see the need to raise awareness amongst the residents on matters relating to the use and maintenance of renewable energy installations, and solar photovoltaic systems in particular.

CHAPTER 5

Costing of interventions



Buildings located in the Greenbelt are located at a fair distance from the nearest low-tension pole or electricity distribution transformer. This part of the paper estimates the costs for connecting each building in the Green Belt to the grid and implementing the solutions proposed in the previous parts, viz. replacing FLA batteries with VRLA batteries, providing a monitoring system at each installation, and installing a shared system of sourcing and storage with Li-ion technology as a pilot system. Cost estimates for each of these are provided in the following pages. Summary given below:

Number of off-grid buildings in Auroville: 130
(Source: Solar Service, Housing Service, TDC, AVES)
Cost of connecting these to the grid:
Rs. 1.5-1.75 crores*
Cost for replacing FLA batteries with VRLA:
Rs. 1-1.25 crores
Pilot centralized system of sourcing and storage:
Rs. 35 lakhs

Note on costs for connecting to the grid:

- Costs of cabling are approximate from a central point in a community to the nearest Low Tension (LT) pole.
- Cost of cabling (calculated only for communities where no building has access to grid-connection yet)
- Cost of on-grid inverters is taken as Rs. 51300 per inverter of Delta brand, and one inverter per installation
- Box, switch, fuse, etc estimated at Rs. 22000 per system
- SPV system installation charges taken as Rs. 5000 per system
- Tamil Nadu Electricity Board charges as Rs. 8000 per connection
- Electrical labour charges at 10% of total cost
- And miscellaneous charges for transport, overtime, etc.

Land footprint has also been calculated according to the type of cabling that will be chosen.

LAND FOOTPRINT	m^2	acres
Aerial cabling:	73,398.00	18.14
Underground cabling:	24,466.00	6.05

Table 5.1

Type A	Site 1	Vikram	Grid supply with a grid fed backup inverter and batteries
	Site 2	Segar	
Type B	Site 1	Bindu	Grid supply with a solar energy-fed backup inverter and batteries
	Site 2	Coriolan	
Type C	Site 1	Vimal	Stand-alone solar PV with an inverter and batteries with no grid backup
	Site 2	Toine	
Type D	Site 1	Auroville Consulting	Stand-alone solar PV with an inverter and batteries with grid backup
	Site 2	Akash	
Type E	Site 1	Toine	Grid-connected solar PV without battery backup
Type F	Site 1	Foundation Office	Grid-connected solar PV with battery backup
Type G	Site 1	Afsanah Guesthouse	Grid connected solar PV with battery backup and diesel generator

Table 5.2

Study of five communities in the Greenbelt, Survey on opinion

Evergreen Community:
Amir & Tamar, Dave & Natasha, Bastian

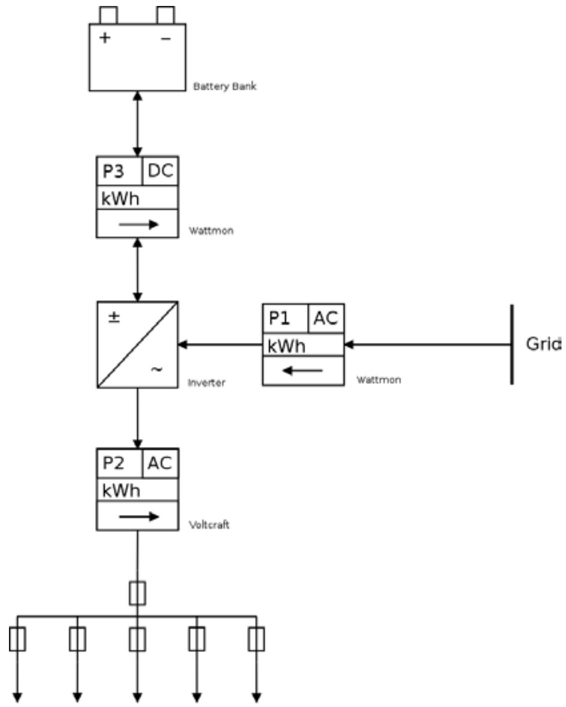
Samriddhi Community:
Alan & Annemarie, Diego, Biggie, Ange and Paul, Shona, Karuna, Ricardo, Guest House (Alan)

Adventure Community:
Kumar, Karthik, Vimal & Paula, Dhruv, Elizabeth, Abbey's House (Sergio), Seyoen

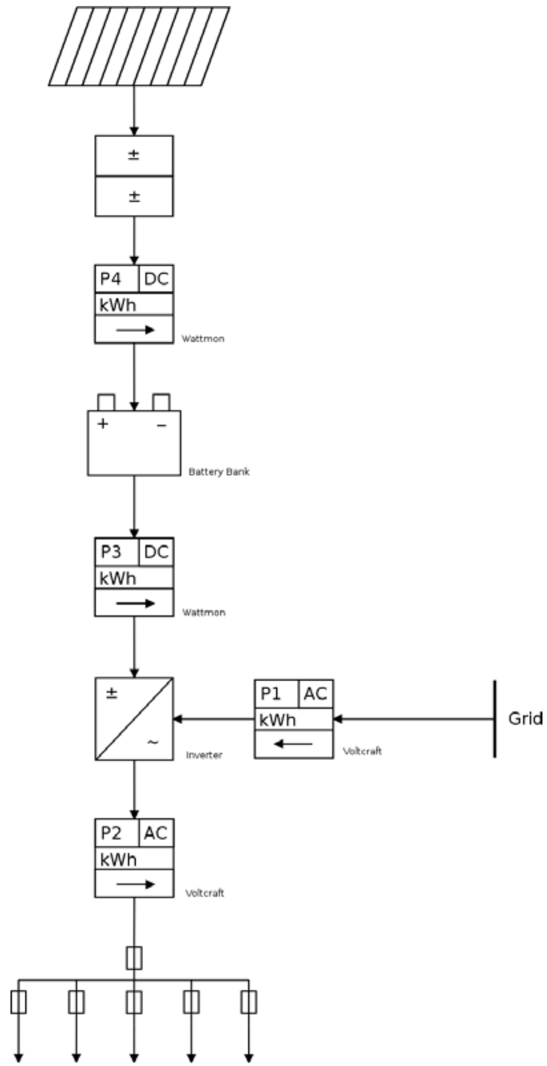
Miracle Community:
Ananda & Kalou, Enea & Ofa

Discipline Farm:
Karin, Stephanie, Joster, Edzard, Meike, Sandeep

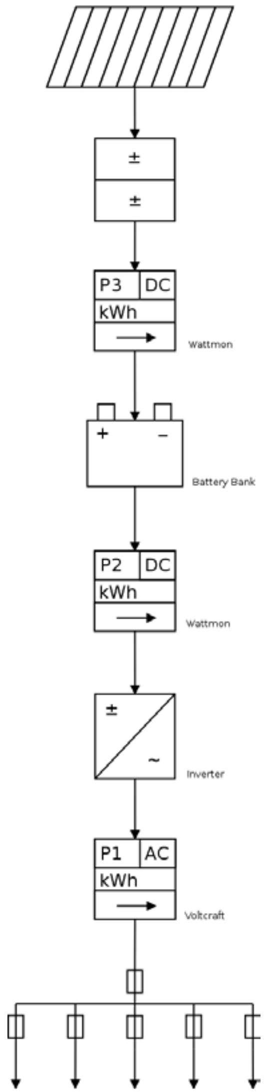
Annexures
Annexure 1: Line diagrams



Type A

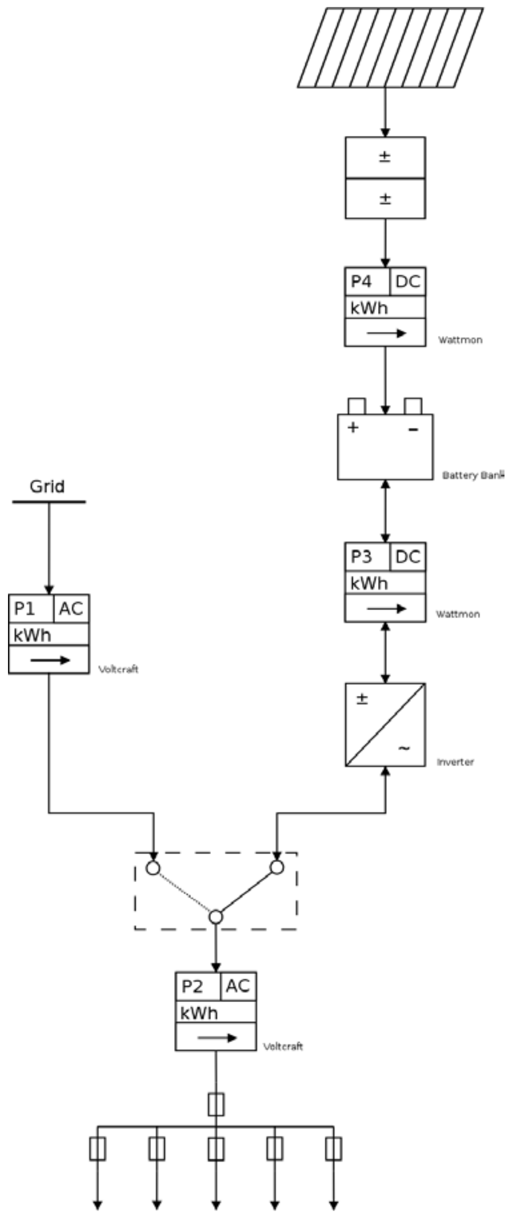


Type B



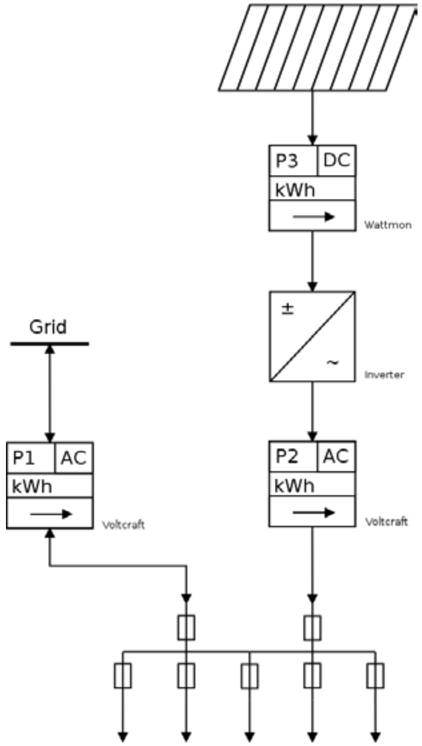
P3
DC
kWh
Wattmon
Battery Bank
P2
DC
kWh
Wattmon
Inverter
P1
AC
kWh
Voltcraft

Type C

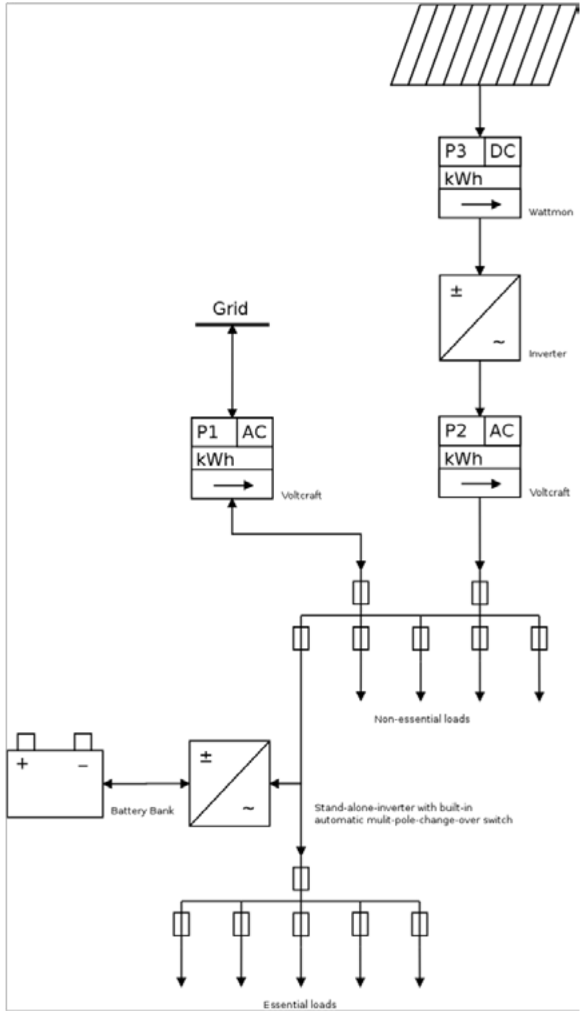


Grid
P1
AC
kWh
Voltcraft
P4
DC
kWh
Wattmon
Battery Bank
P3
DC
kWh
Wattmon
Inverter
P2
AC
kWh
Voltcraft

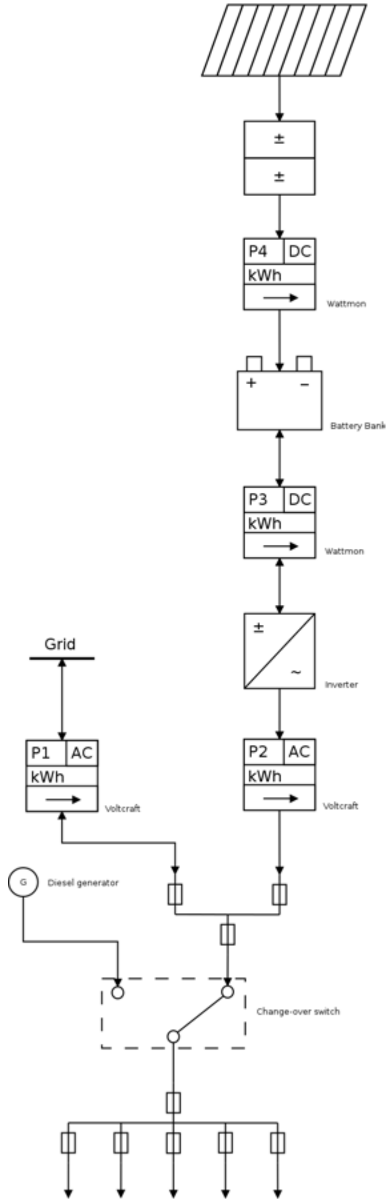
Type D


P3
DC
kWh
Wattmon
Inverter
Grid
P1
AC
kWh
Voltcraft
P2
AC
kWh
Voltcraft

Type E


P3
DC
kWh
Wattmon
Inverter
Grid
P1
AC
kWh
Voltcraft
P2
AC
kWh
Voltcraft
Non-essential loads
Battery Bank
Stand-alone-inverter with built-in
automatic mulit-pole-change-over switch
Essential loads

Type F


±
±
P4
DC
kWh
Wattmon
+
−
Battery Bank
P3
DC
kWh
Wattmon
±
~
Inverter
Grid
P1
AC
kWh
Voltcraft
P2
AC
kWh
Voltcraft
G
Diesel generator
Change-over switch

Type G

Annexure 2: Assumptions for the simulation tool used in technical part

Main assumptions for calculation of overall efficiency were the following:

- As stated before the total efficiency of a system depends on the load profile, which is applied. The load profiles present at Auroville are domestic and office. The profiles were created using sites from the sample, and are detailed below.
- Domestic Profile: Type A Site 2
- Office Profile: Type D Site 1

Week day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Load factor	1.00	1.02	1.21	1.08	1.00	0.98	0.96
Solar factor	1.07	1.07	0.40	0.65	0.98	1.07	1.07
Power cuts	06:29-06:55	13:51-13:56	06:26-07:12	12:02-12:56	05:35-05:56	06:05-06:12	08:09-08:15
	12:23-13:33	15:10-15:47	10:11-10:25	23:00-23:24	09:24-09:40	11:48-12:50	10:33-10:52
	16:29-16:41	20:12-21:00	-	-	12:01-12:33	16:43-17:45	13:02-14:20
	-	-	-	-	23:40-23:43	18:15-18:17	14:05-14:38
	-	-	-	-	-	22:53-22:57	-
	-	-	-	-	-	23:03-23:15	-

Table 5.3: Average week frame conditions for domestic profile

Week day	Monday	Tuesday	Wednesday	Thurs-day	Friday	Saturday	Sunday
Load factor	1.00	1.17	1.18	1.20	1.00	0.51	0.20
Solar factor	1.07	1.07	0.40	0.65	0.98	1.07	1.07
Power cuts	06:29-06:55	13:51-13:56	06:26-07:12	12:02-12:56	05:35-05:56	06:05-06:12	08:09-08:15
	12:23-13:33	15:10-15:47	10:11-10:25	23:00-23:24	09:24-09:40	11:48-12:50	10:33-10:52
	16:29-16:41	20:12-21:00	-	-	12:01-12:33	16:43-17:45	13:02-14:20
	-	-	-	-	23:40-23:43	18:15-18:17	14:05-14:38
	-	-	-	-	-	22:53-22:57	-
	-	-	-	-	-	23:03-23:15	-

Table 5.4: Average week frame conditions for office profile

This system has been chosen for its great availability of data, but did not have solar panels. For the purpose of the study, solar arrays have been scaled accordingly to the load profile.

- Whatever the system Type, all the systems have the same components and the same load profile is applied. Set of components is taken from the sites from which load profile has been extracted.

Component	Parameter	Value
Inverter	Capacity	0.8KVA
	Idle Power	24W
	Eff. conversion to AC	84.6%
	Eff. conversion to DC	67.9%
Battery	Capacity (Type A,D,E,F,G)	150AH
	Capacity (Type B)	300AH
	Capacity (Type C)	600AH
	Voltage	12V
	Eff. conversion energy	72.9%
Solar Array	Peak Power	810W
Usage Parameters	Inverter on time	00:00-24:00
	Battery turn-off SOC	50%
	Grid turn-on SOC	80%
	Grid turn-off SOC	100%
	Night charge interval	19:00-06:00

Table 5.5: Set of components for domestic profile

Component	Parameter	Value
Inverter	Capacity	3KVA
	Idle Power	53.6W
	Eff. conversion to AC	93.3%
	Eff. conversion to DC	91.2%
Battery	Capacity (Type A,D,E,F,G)	75AH
	Capacity (Type B)	150AH
	Capacity (Type C)	300AH
	Voltage	48V
	Eff. conversion energy	79.5%
Solar Array	Peak Power	810W
Usage Parameters	Inverter on time	08:00-18:00
	Battery turn-off SOC	50%
	Grid turn-on SOC	80%
	Grid turn-off SOC	100%
	Night charge interval	19:00-06:00

Table 5.6: Set of components for office profile

The only variation in sets of components is the size of the battery. To keep consistency with environmental part to come, batteries for domestic profile are sized to allow 12 hours of supply in case of Type C, 6 hours in case of Type B, and 2 hours in case of Type A, D, E, F and G. For office profile, they are double sized.

- Frame conditions such as deviations in solar irradiation, load peak usage and occurrences of power cuts are defined.Load factor has been defined according to natural fluctuations in use of electricity; solar factor and power cuts have been measured.
- The simulation of the system works over one week so that conditions from one day affect the next day performance and so on.

Annexure 3: Data used for calculation of energy/carbon footprint

		Energy footprint		Emission factors	
Solar					
Multi-crystalline Si modules	Feedstock			710	kgCO2/kW
	Ingot/crystal + wafer			3687	kgCO2/kW
	Cell			1587	kgCO2/kW
	Laminate			1957	kgCO2/kW
	Total for manufac-turing	820	kWh(p)/m²	14317	kgCO2/kW
	Recycling of Silicon	22	kWh(p)/kWp	7.329	kgCO2/kW
Battery	Manufacturing - from virgin	331	kWh(p)/kWh	95013	gCO2/ kWh(th)
	Manufacturing - from recycled	242	kWh(p)/kWh		
	Recycling of bat-teries	0.688	kWh(p)/kg	0.1610	gCO2/kg
BOS (Balance Of System)	Frame	45	kWh(p)/m²	88.9	kgCO2/kW
	Array support	100	kWh(p)/m²	63.6	kgCO2/kW
	Installation, ca-bling, etc	30	kWh(p)/m²	3.63	kgCO2/kW
	Inverter	350	kWh(p)/kW	124	kgCO2/kW
	Charge controller	330	kWh(p)/kW	950	gCO2/ kWh(th)
	Total for recycling BOS	175	kWh(p)/m²	No data available	

Table 5.7: Set of components for domestic profile

Impact of trans-portation	Impact from trans-portation	0.00504000	kWh/kg*km	0.00009940	kgCO2/ kg*km
	Batteries com-ing from Nandini (133km)	0.67	kWh(p)/kg	0.0132	kgCO2/kg
	Panels coming from Bangalore (372km) and re-cycled in Chennai (160km)	0.23	kWh(p)/Wp	0.0045	kgCO2/Wp
	Inverter com-ing from Delhi (2340km)	141.52	kWh(p)	2.7912	kgCO2
Grid					
Conversion from primary into electrical energy	Efficiency of con-version	32.1%			
	Primary energy needed for manu-facturing 1kWh electrical	3.115	kWh/kWhel	0.950	kgCO2e/ kWhel
Transmission	Losses in transmis-sion in Tamil Nadu	18.5%			
	Primary energy needed (with con-version and trans-mission losses)	3.82	kWh/kWhel		
	Efficiency for con-version and trans-mission	26%			

Diesel generator					
	Efficiency	35%			
	Energy footprint	2.86	kWh/kWhel	1.27	kgCO2/ kWh(el)
Miscellaneous					
	Best thermoelec-tric conversion efficiency	35%			
	CUF (Capacity Uti-lization Factor)	17%			

Annexure 4: Methodology for calculation of energy footprint and carbon footprint of energy systems

Embodied energy of a component [kWh_p]
= (Energy used in manufacturing [kWh_p]
+ Energy used in transport from manufacturing plant to Auroville [kWh_p]
+ Energy used for recycling the component [kWh_p])
x Number of replacements over lifetime

Embodied energy of a system [kWh_p]
= Sum of individual embodied energy per component [kWh_p]

Footprint of net energy imported from the grid [kWh_p]

$$= \frac{\text{Net annual electricity import from grid } [kWh_{el}] \times \text{Lifetime [years]}}{\text{Efficiency of conversion in power plants} \times \text{Efficiency of transmission and distribution}}$$

Footprint of input energy of DG [kWh_p]

$$= \frac{\text{Annual production by DG } [kWh_{el}] \times \text{Lifetime [years]}}{\text{Efficiency of conversion}}$$

Total footprint of input energy [kWh_p]
= Embodied energy of SPV system [kWh_p]
+ Footprint of net energy imported from the grid [kWh_p]
+ Footprint of input energy of DG [kWh_p]

Energy footprint per unit consumed[kWh/kWh]

$$= \frac{\text{Total footprint of input energy } [kWh_p] \times \text{thermoelectric conversion rate [0.35]}}{\text{Annual energy consumed } [kWh_{el}] \times \text{Lifetime [years]}}$$

Payback Period

$$= \frac{\text{Total footprint of input energy } [kWh_p] \times \text{thermoelectric conversion rate [0.35]}}{\text{Annual energy consumed } [kWh_{el}]}$$

For calculation of carbon footprint, the same methodology is adopted, with final carbon footprint calculated as follows:

Carbon Footprint per unit $\left[\frac{kgCO_{2eq}}{kWh_{el}}\right]$

$$= \frac{\text{Total carbon footprint of input energy } [kgCO_{2eq}]}{\text{Annual energy consumed } [kWh_{el}] \times \text{Lifetime [years]}}$$

Annexure 5: Simple Guidelines for Extending Battery Life

- Allow a fully saturated charge of 14–16 hours. Charge in a well-ventilated area.
- Always keep lead acid charged. Avoid storage below 2.10V/cell, or at a specific gravity level below 1.190.
- Avoid deep discharges. The deeper the discharge, the shorter the battery life will be. A brief charge on a 1 to 2 hour break during heavy use prolongs battery life.
- Never allow the electrolyte to drop below the tops of the plates. Exposed plates sulphate and become inactive. When low, add only enough water to cover the exposed plates before charging; fill to the correct level after charge.
- Never add acid. This would raise the specific gravity too high and cause excessive corrosion.
- Use distilled or ionized water. Tap water may be usable in some regions.
- When new, a deep-cycle battery may have a capacity of 70 per cent or less. Formatting as part of field use will gradually increase performance. Apply a gentle load for the first five cycles to allow a new battery to format.
- New batteries with low capacity many not perform as well as those that begin life with a high capacity. Low performers are known to have a short life. A capacity check as part of acceptance is advisable.
- http://batteryuniversity.com/learn/article/water_loss_acid_stratification_and_surface_charge

Annexure 6: Guidelines for Charging Lead Acid Batteries

- Charge in a well-ventilated area. Hydrogen gas generated during charging is explosive.
- Choose the appropriate charge program for flooded, gel and AGM batteries. Check manufacturer’s specifications on recommended voltage thresholds.
- Charge lead acid batteries after each use to prevent Sulfation. Do not store on low charge.
- The plates of flooded batteries must always be fully submerged in electrolyte. Fill battery with distilled or de-ionized water to cover the plates if low. Tap water may be acceptable in some regions. Never add electrolyte.
- Fill water level to designated level after charging. Overfilling when the battery is empty can cause acid spillage.
- Formation of gas bubbles in a flooded lead acid indicates that the battery is reaching full state-of-charge (hydrogen on negative

plate and oxygen on positive plate).

- Reduce float charge if the ambient temperature is higher than 29°C (85°F).
- Do not allow a lead acid to freeze. An empty battery freezes sooner than one that is fully charged. Never charge a frozen battery.
- Do not charge at temperatures above 49°C (120°F). http://batteryuniversity.com/learn/article/charging_the_lead_acid_battery)

Annexure 7: Note on Aqueous batteries (Aqueonenergy.com)

During the course of our research, we came across Aqueous Energy, a company manufacturing "aqueous" batteries, based on saltwater technology. Aquion Energy claims that all raw materials used in the manufacturing process are available in abundance, are non-toxic and low-cost. If these claims are indeed true, then these batteries could be a viable alternative to Li-ion batteries.

A quick summary of the main parameters, as given on their company website:

Technical parameters

- Safety: no hazardous materials, corrosive acids or noxious fumes
- Steady capacity up to 5000 cycles
- High cycle life @ 100% DoD (3000 cycles)

Social parameters

- Performs well at partial state of charge with minimal degradation
- No corrosive reactions: safe to handle; not flammable or explosive
- Claim to be reliable
- Designed for use in a micro-grid (centralized small-scale storage system)
- No regular maintenance required

Economical parameters

- Claims to have a lower $/kWh than lead acid or lithium-ion batteries

Environmental parameters

- Composed of saltwater electrolyte, manganese oxide cathode, carbon composite anode and synthetic cotton separator.
- No deterioration of materials during use and no corrosive reactions. Batteries function from -5°C to 40°C.
- Since temperatures in Auroville exceed this limit, the system will need well ventilated area and shade.Annex: Guidelines for maintaining SPV Panels
- Inspect panels regularly to check if there is no debris or dirt
- Ensure all connections are tight

- Clean the panels in the morning or evening;
- Avoid the use of cold water on hot panels as this could crack the panels
- Install a water harvesting system to gather water obtained from cleaning the panels
- Rainwater leaves deposits on the panels that need to be washed away with water (http://www.solar-facts-and-advice.com/solar-panel-cleaning.html).

Annexure 8: Survey Questionnaire

Section	Item
General	Community
	Sunlit code
	Tele
	Email
	How many adults
	How many children
	How many people (total)
	Photos of SPV Setup
Building and site details	Type of site (House, Office…)
	Is there a battery? (1/0)
	Is there a solar panel?(1/0)
	Is the building connected to the grid? (1/0)
	Does the grid charge the battery? (1/0)
	SPV installation export to the grid?(1/0)
	Is there a diesel generator?(1/0)
	System Code[Auto Filled]
	System Type [Auto Filled]
	Distance to nearest LT pole
	Distance to nearest transformer (m)

Table 5.8

Section	Item
System overall	Who installed the system?
	Is the wiring well done? (Agree/Disagree)
	Who is maintaining the system?
	Is the system maintained well? (1 to 5, 5 is highest)
	Average daily energy consume (kWh)
	System sufficient for current needs? (1 to 5, 5 is highest)
	Capacity addition to make the system sufficient for current needs? (%)
Inverter details	Inverter make
	Model
	Inverter KW (KVA)
	Inverter kVA/person
	Offline or online (OFF/ON)
	Inverter DC Voltage (V)
	Inverter AC Voltage (V)
	Inverter with grid charging option? (Y/N)
	Inverter with grid export option? (Y/N)
	Year of make (yyyy)

Section	Item
Panel details	How many kinds of SPV Panels Installed
	SPV Panels 1st make
	2nd make
	3rd make
	Type of SPV panels(Mono,Poly,Hybrid)
	Type of mounting structure(Roof/Ground)
	Is there shade on the panels?
	Wattage of each SPV Panel (average, W)
	Number of SPV panels
	Total Solar Power (Watt) [Auto]
	Estimate of daily SPV Energy Generated (kWh)
	Estimate of energy generated per annum (kWh)
	Number of units per person per annum
	Year of installation (yyyy)
Battery details	Batteries make
	Battery type (lead acid/lithium ion)
	Battery bank voltage (V)
	Number of batteries
	Capacity of each battery(Ah)
	Total battery bank capacity (Ah) [Auto Filled]
	Energy Storage capacity (kWh) [Auto Filled]
	Battery maintenance by?
	If FLA type: in a ventilated or open space?
	Year of installation (yyyy)

Section	Item
Charge controller	Is there a separate Charge controller? (Y/N)
	Charge controller make
	Charge controller Model
	Charge controller type (PWM/MPPT) [Optional]
	Capacity [Maximum Battery Current] (A) [Optional]
	Maximum Solar Input DC Voltage (V) [Optional]
	Maximum Battery Output DC Voltage (V) [Optional]
	Year of installation (yyyy)
Monitoring	Platform
	Solar charge current sensor
	Inverter drain current sensor
	Charging current sensor (Y/N)
SPV system config	Uses only pump
	Primary source is grid, back up source is solar, has inverter and batteries
	No grid connection, has solar pv, inverter and batteries
	Primary source is solar pv, has inverter and batteries, grid connection is backup
	Primary source solar pv, no Inverter, has battery, no grid back up
	Has grid connection, solar pv and inverter and batteries
	Has grid connection, solar pv and inverter, and diesel generator

Section	Item
Battery	Cracks in the battery container
	Are batteries and connections clean and free of dirt and corrosion
	Is there any fluid on or around the battery
	Are there any loose or damaged parts in the battery cables and their connections
	Are there any loose wiring
	Is there space for additional batteries:
	Is there space between the batteries for battery expansion?
Mounting	Is the structure on which the solar panel mounted strong?
	Does the structure tremble or shake when force is applied?
	Are all the bolts, nuts, fasteners and clamps in good condition?
	Is there seepage or dripping of water from the sides of the panel or groove holes?
Panels	Is the space clean of dust and dirt?
	Is there convenient access to the SPV system:
	Are the solar panels accessible for cleaning?
	Are there any natural or man-made shading on the solar panels?:
	Are the solar panels accessible from the bottom to gain access to the junction box:
	Are the panels clean and free of dust/dirt?
	Is there a person to maintain the cleanliness of the SPV system and solar panels?
	Are the solar panels cleaned and maintained regularly?
	Direction the panels are installed?

Section	Item
	Angle of installation? (°)
	Are there layout drawings?
Cabling	Are all the wiring passing through PVC conduit pipes?
	Are all the wiring secured by staples, cable ties, straps, hangers or similar fittings?
	Are there any wires that are bending too much?
	Are there any wiring that is fastened too tightly or too loosely?
Protection	Is there a DC surge protection?
	Is there a AC surge protection?
	Are there DC fuses or Miniature Circuit Breakers (MCB's)?
	Is there a lightning protection for the SPV system?

Anexxure 9

- Deep-cycle: use of a battery fully charging it and discharging it (usually one cycle equals one day)

- Discharge rate: Often expressed as a rate of capacity (C-rate), a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100Ah, it equates to a discharge rate of 100A (as well a C/2 rate would be 50A). (http://web.mit.edu/evt/summary_battery_specifications.pdf)

- DoD, short for the Depth of Discharge, is used to describe how deeply the battery is discharged. If we say a battery is 100% fully charged, it means the DoD of this battery is 0%, If we say the battery have delivered 30% of its energy, here are 70% energy reserved, we say the DoD of this battery is 30%. And if a battery is 100% empty, the DoD of this battery is 100%. DoD always can be treated as how much energy that the battery delivered (http://www.bestgopower.com/faq/frequently-asked-questions/depth-of-discharge.html). The percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A discharge to at least 80 % DoD is referred to as a deep discharge (web.mit.edu/evt/summary_battery_specifications.pdf)

- ESOI, standing for Energy Stored On Investment. The amount of energy that can be stored by a technology, divided by the amount of energy required to build that technology

- Flooded lead acid batteries: are called “flooded” because the plates are submerged in an excess of electrolyte, which compensates the water loss during charging.

- Life Cycle: The number of cycles, to a specified depth of discharge, that a battery can undergo before failing to meet its specified capacity or efficiency performance criteria
- LiFePO4 cathodes (also named LFP, standing for Lithium Ferro Phosphate): Type of lithium-ion battery using LiFePO4 as a cathode material. It has somewhat lower energy density than more common LiCoCO2 found in consumer electronics, but offer longer lifetime, better power density (the rate that energy can be drawn from them) and is safer. It is then very suitable to backup power use. (http://en.wikipedia.org/wiki/)

- Self-discharge: Capability of a battery to lose a certain amount of energy stored when not used

- Specified capacity: Amount of charge available expressed in Ampere-hours (Ah). The capacity is measured by discharging at constant current until it reaches its terminal voltage, under standard temperature of 25°C. The capacity is calculated by multiplying the discharge current value by the time required to reach terminal voltage. (http://www.engineersedge.com/battery/capacity_battery_ratings.htm)

- State of charge: An expression of the present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine the change in battery capacity over time. http://web.mit.edu/

- Thermal runaway: Thermal runaway refers to a situation where an increase in temperature changes the conditions in a way that causes a further increase in temperature, often leading to a destructive result. It is a kind of uncontrolled positive feedback (http://en.wikipedia.org/wiki/Thermal_runaway). A process which is accelerated by increased temperature, in turn releasing energy that further increases temperature

- Valve-Regulated Lead Acid: VRLA have the ability to recombine oxygen with hydrogen to create water; which prevents the system from water loss. Surplus gas is vented when the internal pressure gas builds up.

- http://www.coresite.com/resources/faq-what-is-kva. A KVA is simply 1,000 volt amps. A volt is electrical pressure. An amp is electrical current. A term called apparent power (the absolute value of complex power, S) is equal to the product of the volts and amps.

- On the other hand, a watt (W) is a measurement of real power. Real power is the amount of actual power that can be drawn from a circuit. When the voltage and current of a circuit coincide, the real power is equal to the apparent power. However, as waves of current and voltage coincide less, less real power is transferred, even though the circuit is still carrying current. Differences between real and apparent power, and thus watts and volt amps, arise because of inefficiencies in electrical transmission.

- The resulting inefficiency of electrical transmission can be measured and expressed as a ratio called the power factor. The power factor is a ratio (a number from 0 to 1) of real power and apparent power. In the case of a 1.0 power factor, the real power equals the apparent power. In the case of a 0.5 power factor, real power is approximately half that of the apparent power.

Anexxure 10

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