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Multi-Criteria Storage Selection Model for Grid-Connected Photovoltaics Systems

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ABSTRACT The grid-connected photovoltaics (GCPV) systems are a sustainable alternative to the conventional non-renewable electricity systems. However, GCPV systems create the many issues such as grid overloading, demand and supply variations, and power quality issues. A key way to address such issues is the integration of the effective energy storage technologies in GCPV systems. There are many storage technologies which can be connected with GCPV systems. The integration of a proper storage technology into the GCPV systems may provide a best alternative. This paper evaluates the different storage technologies for GCPV systems using the analytic hierarchy process (AHP) approach. The goal of the AHP model was the selection of the best storage alternative for GCPV systems based on the multiple criteria. The criteria included the storage parameters as well as the parameters related to the compatibility with GCPV systems. The results exhibited that the pumped hydro storage is the best alternative if all the storage and compatibility parameters are equally desirable. However, if AHP model gives the highest preference to the criteria ''integration simplicity regarding renewable energy'' and ''geographic limitations'', the several other storage technologies achieve the higher rankings. Hence, the AHP model provides a greater flexibility to evaluate the different storage technologies for GCPV systems under different circumstances.

INDEX TERMS Analytic hierarchy process (AHP), electrical power grid, environmental sustainability, power flow balancing, power system planning, power system reliability, renewable energy, solar energy, PV.

I. INTRODUCTION

The conventional electricity generation involves the higher inputs of the fossil fuels, resulting in the higher environmental pollution [1]. The fossil fuels are the major sources of the environmental pollution [2] as well as the key sources of the electricity production in the world. Gradually, the fossil fuels are depleting and the electricity demand is increasing [3]. In addition, the scarcity of the fossil fuels results in an increase in their prices [4]. As a result, many communities in many countries are unable to satisfy the full electricity demand from their national grids [5]. Moreover, the share of the sustainable and renewable power is very low in the national grids [6]. For instance, the share of the renewable energy (excluding hydropower) in Pakistan is approximately 2% [7]. In contrast, the share of the renewable energy (including hydropower) in Bangladesh is 3% [8]. To overcome the above challenges, the grid-connected solar photovoltaics (GCPV) systems are offering the endless and clean power supply to consumers and the national grids. The photovoltaics (PV) systems are gaining a significant importance due to the remarkable solar energy potential and the technological advancements [9]. Besides, the economic viability of PV systems has been appreciated by many countries [10] such as Nigeria [11] and Ethiopia [12]. In contrast to the off-grid PV systems, GCPV systems offer the storage of the extra PV power into the utility grid [13]. In addition, the integration of the other storage technologies into GCPV systems is more cost effective than off-grid systems. For instance, Reference [14] studied a grid-connected PV system with battery storage and concluded that the proposed system offers the remarkable cost savings related to off-grid system.

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The GCPV system consists of the photovoltaics (PV) modules, connection with a utility grid, and consumer loads. The PV modules generate the highly fluctuating output that is not suitable for consumer usage and the grid export [15]. To overcome this challenge, the electricity is sold to the utility grid during the peak PV generation times and it is purchased from the utility grid during the off-peak times. However, the grid may be unable to provide the required electricity at off-peak times or the higher feed-in of PV into the utility grid may cause the grid overloading [15]. In such situations, a proper storage system provides the many benefits such as PV variability management [16], stabilization of the power system [17], storage of excessive electricity [18], additional inventory for the times of electricity shortage at the utility grid [19], reduction of electricity procurement from the utility grid [20], load management flexibility, and solutions to the power quality issues [21]. Hence, the proper storage technologies will be the integral components of the future grids.

The existing literature regarding GCPV systems prefers the battery storage in the industrial and residential communities due to the advantages such as high modularity [22], compactness, integration simplicity, construction simplicity, safety [23], and power regulation [24]. However, the battery storage technology has been identified as a costly option [25]. For instance, Reference [26] evaluated the economic viability of a GCPV system with battery storage and concluded that the proposed system is not profitable without the financial support. The high cost issue may be a key hurdle in the adoption of the renewable energy based power systems. In this context, only a few criteria (e.g. cost or modularity) should not be a sole reason to accept or reject a storage technology. The decision making should contain all the key quantitative and qualitative criteria. A good storage technology should retain the acceptable storage parameters in addition to the compatibility with GCPV systems.

Historically, only the quantitative factors, such as cost and time, were the focus of the decision making. Many important issues were ignored in the decision making. The elimination of some important quantitative and qualitative factors may lead to the improper decision making. For instance, the optimal and exact solution based only on the cost may not be an acceptable solution if other more important criteria have been ignored. The selection of the storage systems in the grid connected power systems is a complex decision making process which should include all the important qualitative and quantitative factors. Multi-criteria problem with many quantitative and qualitative criteria may not be solved based on the simple optimization. The single criterion decision making methods cannot solve many conflicting objectives efficiently. To solve such problems, the multiple criteria decision making (MCDM) methods can be used. This paper used AHP (analytic hierarchy process) method which is an extensively used technique for solving MCDM problems. AHP is a heuristic algorithm which provides the approximate solution of the problem. Hence, the solution optimality is not guaranteed. However, the achievement of the exact solution of the problems with many qualitative and quantitative criteria is very difficult. In this case, heuristic methods provide the approximate solution. Recently, the storage selection for the GCPV system is a strategic decision in which approximate solution based on all the important criteria will provide a good information for the decision making.

The present paper solves the multi-criteria storage selection problem using AHP approach. AHP method has been used for numerous projects with high cost. For instance, there are 56,000 deficient bridges in the United States, which require a considerable investment. Due to budget constraints, it is not possible to repair every bridge. Reference [27] used AHP method to prioritize those deficient bridges using four intangible criteria including safety, serviceability, comfort, and resiliency. The model assigned the highest preference to the criterion ''safety''. In the multi-criteria decision making literature, AHP approach has been used in the numerous applications such as selection of PV plant location [28], selection of renewable energy resources for the power system [29], and the evaluation of energy technologies [30]. The many papers used AHP approach for the decision making in the power system problems, such as site selection for power plants [31], the evaluation of renewable energy resources [32], and the evaluation of PV systems [33]. For instance, Reference [34] used AHP method to evaluate the renewable energy resources in the developing countries. It was concluded that the hydro energy resource is the best alternative. However, this priority was changed based on the technological advancements and geographical locations.

AHP approach is a structured and proven approach for complex decision making, which allows the integration of the qualitative and quantitative data [35]. The present paper implements the AHP model in Super Decisions software. AHP method was developed by Thomas L. Saaty. His team created Super Decisions software to implement AHP method due to the complexity of AHP method. Hence, the proposed software facilitates the quick implementation of the AHP method. This software has been used to solve the various AHP models. For instance, Reference [36] applied AHP method in super decisions software for the selection of the best standalone renewable energy system in South Sudan. The results indicated that the PV system has a first priority at all the selected locations in South Sudan. In the existing literature, no study evaluated the different storage technologies for the GCPV systems using AHP approach. Hence, the present paper used AHP method to evaluate the different storage systems for the GCPV systems based on the various criteria and circumstances. This paper evaluates the different storage technologies in the GCPV systems based on the multiple criteria. These multiple criteria included the eight quantitative storage parameters and six qualitative factors related to the compatibility with GCPV systems. The eight quantitative criteria are the frequently listed parameters in the literature. The compatibility factors included the six criteria and 15 sub-criteria for important issues related to GCPV systems with storage.

II. GCPV MODELS WITH STORAGE

In an effort to identify a proper storage technology for the GCPV systems, many papers evaluated the different storage technologies which can be integrated into the GCPV systems. This section summarizes the results of the existing literature related to the GCPV models with storage technologies.

A. GCPV SYSTEMS WITH BATTERY STORAGE

Most of the research used the battery storage technologies in the modeling of the GCPV systems [37]. The extensive use of the battery storage technologies in PV systems is due to the advantages such as the easy availability and integration [38]. In many countries, PV owners are increasing self-consumption through the battery storage technologies [39]. Previously, these countries motivated PV owners for the electricity sharing with utility grids through the incentives such as feed-in-tariff. Gradually, these incentives are decreasing for the grid-connected renewable energy based power systems, resulting in more self-consumption [40] and less grid import due to an increase in the electricity prices [41]. To study GCPV systems, many researchers have evaluated GCPV system with battery storage. For instance, Reference [20] proposed a GCPV system with battery storage to determine the optimal sizing of PV system and battery storage. They proposed a feed-in tariff policy which resulted in the 79.8 megawatt-hour PV power import from the utility grid but only 1.55 megawatt-hour export to grid. Hence, a proper battery storage capacity can decrease the power export to the grid and increase the self-utilization of PV. Battery storage technologies are providing the benefits in many other ways. For example, Reference [24] suggested that the time-of-use rate offers the more economical adoption of the PV system with battery storage than flat rate. Also, Reference [42] evaluated a grid-connected system in which a residential PV owner with battery storage shared PV power with a commercial PV owner. They achieved the daily cost savings between 31% and 81% with reference to using only the utility grid.

The small scale and large scale PV systems with battery storage may provide different outcomes. The battery storage systems can be used in the high voltage requirements in the GCPV [43]. Reference [44] evaluated an optimization model to identify the factors affecting the profit of the grid-connected, battery assisted residential PV configurations in Germany. They concluded that these configurations are not profitable for small scale systems. However, these may become more attractive if the cost of PV installations and storage systems becomes lower. They suggested that these configurations may be profitable if larger PV systems are combined with proper size of storage systems. However, it is evident that the grid-connected large PV plants with heavy battery storage system are also costly. For instance, Reference [45] simulated the integration of 1 MW/ 2MWh Li-ion battery system with a grid connected 10 MW PV plant. In the proposed configuration, the batteries were used to store extra energy during higher PV output and they discharged the energy to grid during off-peak PV generation. The battery system was connected to a grid through an inverter. The results showed that the battery storage system may not be feasible for the proposed system. In this case, battery storage systems require more incentives to promote the PV systems.

Many scholars have reported the various advantages of the battery storage in the GCPV systems such as quality, stability, [46] reliability [47], demand and supply balance, and power reserve [48]. Also, many scholars have reported the high cost of the battery storage technologies. Many GCPV models with battery storage have concluded that the integration of the battery is expensive due to the high storage costs such as the battery replacement and maintenance costs. For instance, Reference [49] concluded that the battery storage in the PV systems is expensive than grid export. For example, Reference [50] evaluated the optimal power flow between PV plant, grid, batteries, and consumer demand. The objective was to minimize the electricity bill. They concluded that the proposed system is not the cost effective due to the high cost of the battery replacement costs but it may be cost effective in future if the electricity prices increase. Hence, the battery replacement cost is unacceptable even if the batteries do not store electricity for the utility grid. In contrast, the battery storage has increased the self-consumption of the PV system owner as discussed above. For instance, Reference [51] performed the cost analysis of a grid-connected residential PV with battery storage size optimization. To increase the self-consumption of the residential load, the PV power was exchanged with grid only after the battery became full or empty. The results revealed that the storage cost is higher, and these systems can be promoted through the proper incentives. It was found that the GCPV without battery storage is more economical than the battery storage. It was also concluded that the lithium ion battery storage is more economical than lead-acid storage due to the fact that the lead-acid batteries involve the more number of replacements. In another study related to the GCPV, it was concluded that the battery storage cost was more than the grid related costs and benefits. The study highlighted that the inclusion of the battery system may be more preferable in future if the capital and maintenance costs related to batteries decrease continuously. Hence, the battery storage system seems an immediate solution in case of unattractive feed-in tariff, less pricing benefits from national grid, and continuous decrease in the battery cost [52]. For instance, Reference [53] proposed an optimization model of PV system with grid connection. They revealed that the battery storage is preferable if the feed-in tariff becomes unattractive. In addition, with an increase share of the renewable electricity, the benefits associated with national grid may be decreased in future [49]. Recently, the integration of the battery storage into the residential GCPV systems seems uneconomic [54]. Hence, alternative strategies are required to accelerate the utilization of renewable resources.

B. GCPV SYSTEMS WITH PUMPED HYDRO STORAGE

Many mathematical and simulation models used the pumped hydro storage in the GCPV systems. These models suggested that the GCPV systems with pumped hydro storage offer a reliable storage technology for the proposed systems [55]. Reference [5] optimized a grid-connected system involving PV system, pumped storage, and a farming load. In the proposed system, the PV electricity served mainly to a farming load. The excess PV electricity pumped the water towards an upper reservoir. This stored water was used to generate electricity at the times of PV shortage. The pump and farming load obtained the electricity from grid when the price of grid electricity was low. It was concluded that the proposed system minimized the power import from utility grid in addition to the cost savings. Hence, the pumped storage works as both electricity generator and the storage technology. In addition, this system provides cost saving through the minimization of the grid electricity import. Similarly, Reference [56] simulated a grid-connected PV scheme with pumped hydro storage (PHS) for a farmhouse. They concluded that the pumped hydro storage has significantly reduced the yearly electricity cost. The GCPV system with pumped hydro storage has two sources of electricity generation, resulting in less import from the utility grid. Also, Reference [57] presented a GCPV with pumped hydro storage. The excess PV generation was used for water pumping to upper reservoir or for selling to the utility grid. At the times of little or no PV generation times, the load was satisfied by the pumped system or grid. They optimized the electricity purchased from grid to minimize the operation cost. They concluded that the daily operation cost for load satisfaction by only grid power is 70.7 $ when the PV is not available. In contrast, this cost is 33.3 $ for the PV system with pumped storage. Reference [58] proposed an optimization model to minimize the grid power using time-of-use tariff in a GCPV systems with pumped hydro storage. The proposed system resulted in the remarkable cost savings with reference to the grid power. Hence, GCPV systems with pumped hydro storage offer the remarkable cost savings compared with the electricity from utility grid. Reference [59] evaluated the feasibility of the grid-connected PV system with lithium-ion battery and pumped hydro storage. It was concluded that the pumped hydro storage has an optimal configuration and the battery storage was costly.

In the pumped hydro storage, the energy is stored as the potential energy as a result of water pumping from lower to upper reservoir [57]. Hydro storage is a long term solution to stabilize the GCPV system. This system requires a higher investment but these investments can be recovered in the long term [58]. Pumped hydro storage involves the geographic restrictions related to the water availability, land availability, and geographical height [57]. Hence, it can be implemented at specific places such as farm houses with a reasonable amount of water [60]. The geographical limitations or the location issues associated with pumped storage system may decrease its priority.

C. GCPV SYSTEMS WITH SUPERCAPACITOR AND FLYWHEEL STORAGE

The hybrid battery-supercapacitor storage technology can be used to balance the power flow in the GCPV systems. For instance, Reference [61] simulated a GCPV with hybrid battery and supercapacitor storage. In the proposed system, the storage devices were used between the PV and grid. The supercapacitors were used to reduce the stress level of batteries and increase the battery lifetime. The hybrid storage technology successfully supplied the smooth power from PV system to the utility grid. Reference [62] simulated the power fluctuations for a GCPV system using hybrid storage technology with the battery and supercapacitor. The results exhibited that the hybrid storage technology decreased the power fluctuations in the GCPV. Hence, the voltage fluctuation of PV system can be decreased with a storage technology containing battery and supercapacitor. The battery storage has a high energy density and supercapacitor storage has a high power density [63]. As a result, the hybrid battery and supercapacitor can decrease the power fluctuations in addition to the battery life improvements [64]. In addition, the supercapacitors improve the frequency response of the battery storage system [65]. Reference [66] evaluated a grid-connected 1 MW PV system with hybrid battery and supercapacitor. They concluded that the proposed system performed better than the alone battery or supercapacitor. The supercapacitor reduces the charging and discharging cycles of battery, resulting in the extension of battery life [67].

The flywheel storage has been used as a short term power storage to handle the PV fluctuations [68]. Reference [69] highlighted that the flywheel storage provides the better performance related to the power flow variations, quality, and frequency control. Most of the research combined flywheel with battery storage to improve the battery duration in the GCPV systems. Flywheel storage is used to increase the battery life [70]. Flywheels are considered as an ecofriendly technology due to their recyclability and absence of chemicals [71]. Flywheel storage performs peak shaving in GCPV systems with battery storage [72]. The combined effect of battery and flywheel involves the cost savings [73]. Integration of flywheel storage offers 20% increase in battery life [74].

D. GCPV SYSTEMS WITH COMPRESSED AIR ENERGY STORAGE

Usually, the small scale grid-connected systems are used to reduce the electricity bills. In contrast, the large scale PV plants provide the electricity to the large communities and industries. Compressed-air storage has been recommended as large scale storage in GCPV system [75]. There is a lack of literature regarding the GCPV systems with compressed air storage [76]. Reference [77] evaluated a 100 MWp GCPV plant with compressed air energy storage. The proposed system exhibited the 16% energy efficiency and payback time of nine years. Hence, this storage technology can be used for large scale PV plants. For instance, the super grids between large distances may require the large scale PV plants with

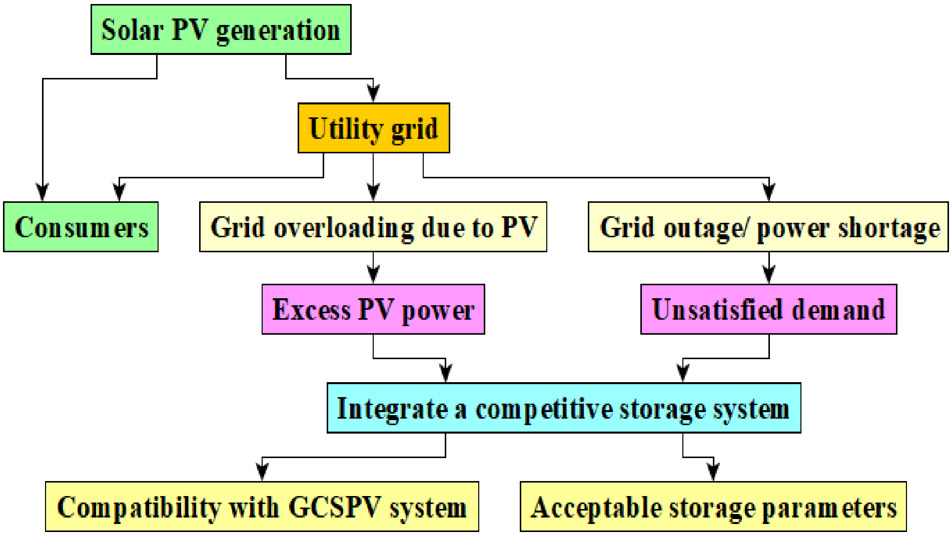


FIGURE 1. Storage technology integration with GCPV system.

large scale storage systems. In this regard, the large scale storage technologies, such as the compressed air storage and the hydrogen storage, may be recommended as long term or seasonal storage.

E. GCPV SYSTEMS WITH HYDROGEN STORAGE

The battery storage is recommended as short-term storage but hydrogen storage is recommended as long term or seasonal storage. However, the hydrogen storage has a round-trip efficiency of 35% which is very low than the battery storage systems. Research has exhibited that batteries stored less energy than the hydrogen storage. Reference [78] evaluated a GCPV and found that the hydrogen storage decreased grid fluctuations more than the battery storage. The hybrid battery and hydrogen storage increases the stability in the GCPVs with reference to only battery storage [79]. Hybrid battery and hydrogen storage results in higher incomes.

Pumped hydro storage and compressed air storage are the large scale energy storage technologies, but they have the limited applications in the GCPV systems due to the geographic constraints. In contrast, hydrogen storage is a large scale energy storage technology without geographic constraints [80]. Hydrogen storage with fuel cells offers the energy density of 3000 Wh/L, life cycle of 1000 cycles, discharge duration of 8 hours [81], and life time of 20 years [82].''

III. STORAGE INTEGRATION IN THE GCPV SYSTEMS

In the existing literature, it can be observed that the battery storage technologies have been used frequently in the GCPV models [83]. Hence, the battery storage looks the better alternative for PV output [84]. For instance, Reference [85] performed the dynamic simulation on a system containing PV panels, battery storage, and hydrogen based storage for residential demand. In the suggested scheme, PV output charged the battery and the excess power was converted into hydrogen fuel. It was highlighted that the battery systems are more suitable for PV than the hydrogen storage, pumped hydro, and compressed air energy storage systems. Furthermore, the round trip efficiency of the batteries is between 75-90% while this efficiency is only 30% for hydrogen storage. Hence, battery storage is a comparatively better system for PV output than other types of storage technologies [86]. However, some literature reported the superiority of the other storage technologies on the battery storage [78]. Hence, the integration of other storage technologies must be considered for the possible integration into the GCPV systems. For instance, the battery storage systems may be very costly for the large scale GCPV systems, such as super grids.

Each storage technology has the many different characteristics which affect the power systems. For example, Reference [87] compared the different energy storage systems for a utility-scale GCPV system based on discharge duration time, efficiency, life time, and cost. They highlighted that the small pumped hydro has the longest duration of 8 hours, lithium ion batteries have highest efficiency of 94%, flywheel has longest life time of more than 100000 cycles, and cost per kWh is comparable for the pumped hydro, compressed air energy storage, and sodium sulfur batteries. Hence, the decision making should consider all the important characteristics for the selection of a comparatively better storage technology for GCPV systems. Hence, this paper evaluates the different storage technologies in the GCPV systems based on the multiple criteria including the storage parameters and the factors related to the compatibility with GCPV systems.

Figure 1 presents the concept of the storage technology integration in the GCPV systems. Table 1 has been developed based on the maximum values of the eight storage parameters available in the existing literature. The data in Table 1 was collected from research papers and other possible secondary data available in the literature. Specifically, the parameters for pumped hydro, compressed air, and sodium sulfur battery

TABLE 1. Quantitative parameters of storage technologies.

	Lifetime (LT1) (years)	Discharge Duration (DD) (hours)	Discharge Efficiency (DE) (%)	Round-trip Efficiency (RTE) (%)	Lifetime (LT2) (cycles)	Capital Cost (CC) (USD/kW)	Energy Density (ED) (Wh/L)	Power Rating (PR) (MW)
Pumped hydro storage (PHS)	60	8	87	85	50000	2000	2	5000
Compressed air storage (CAS)	40	5	79	89	30000	1350	20	400
Flywheel (FW)	20	0.25	93	95	100000	450	424	20
Supercapacitor (SC)	30	0.17	98	98	100000	500	35	0.10
Lithium ion battery (LIB)	16	4	85	97	20000	4000	50	100
Lead acid battery (LAB)	15	4	85	90	2000	800	90	40
Flow battery (vanadium) (FBV)	20	4	82	85	16000	2500	90	100
Sodium sulfur battery (SSB)	20	7.2	85	92	5000	3000	345	34
NiCd battery	20	4	70	90	3000	1500	150	50
Zinc-Bromine flow battery (ZBFB)	20	8	70	75	3500	2500	70	10
Hydrogen fuel cells (HFC)	20	8	59	47	1000	3000	3000	50

were obtained from Reference [84]. Similarly, the parameters for flywheels and NiCd battery were obtained from Reference [87]. The parameters for Lithium ion battery and flow battery (vanadium) were obtained from Reference [88]. The data for supercapacitors was obtained from Reference [89]. The data for Lead acid battery and Zinc-Bromine (flow battery) was obtained from Reference [90]. The data from these references was verified between these papers as well as other secondary literature. The maximum values or upper limits of all the parameters were used in AHP model. Table 2 evaluates the qualitative compatibility criteria based on the three assessment levels including highly promising or experienced (H), moderately promising (M), and least promising or infeasible (L). The maximum qualitative compatibility criteria and the three assessment levels were adapted from the Reference [91]. In addition, many other papers were reviewed for the missing data, specifically compressed air energy storage [92], some qualitative items reference [93], supercapacitor-based energy storage [94], pumped hydro energy storage [95], and hydrogen storage [96]. The input data related to criteria "Geographic limitations" and "Toxic effects of storage technology" were included based on the evidence from the related literature.

The environmental sustainability criteria should be included into the decision making. The PV power is an environment friendly technology and the storage technology should also be the compatible with environment. For the environmental sustainability, this paper gives the higher preference to the three factors, specifically the lifetime (in years), lifetime (in cycles), and the toxic effects of the storage technology. The materials used for a storage system cause pollution during the different stages of the product supply chain. The short lifetime causes the frequent production of different materials. For instance, the battery utilization at the grid level will accelerate the frequent manufacturing of the required number of batteries. In contrast, the compressed air and the pumped hydro involve the minimum replacement of the related materials due to the more lifetime [82]. The criteria "Toxic effects of storage technology" is also a major environmental issue. For example, Lead acid and Nickel Cadmium (NiCd) batteries contain very toxic heavy metals including Lead and Cadmium.

The lithium-ion batteries are the less toxic than the lead acid batteries. However, all the batteries produce hazardous pollution during the manufacturing, use, and disposal stages [97]. The pumped hydro and compressed air energy storage involve the negligible toxicity compared with the batteries [82]. Similarly, hydrogen storage has no disposal issues related to the toxic pollutants [98].

IV. ANALYTIC HIERARCHY PROCESS (AHP) MODEL

This paper evaluates the different storage technologies for GCPV systems using an analytic hierarchy process (AHP) model. Figure 2 presents the complete hierarchy of the AHP model. The symbols used in the hierarchy have been defined in Table 1 and Table 2. The proposed AHP model used the storage criteria in Table 1 and compatibility criteria in Table 2. AHP model can be developed manually or in the spreadsheets. However, it involves the time consuming calculations. As a result, many software packages have been developed to implement the AHP method. The present paper used the software package "Super Decisions" to implement the storage system selection model. This free software has been used in many applications for the complex decision making [99].

The mathematical theory [100] and the detailed algorithm [101] of AHP method can be found in the relevant literature. In the following, key steps have been presented [102].

TABLE 2. Qualitative factors related to storage compatibility with GCPV systems.

	Pumped hydro	Compressed air	Flywheel	Supercap acitor	Lithium ion battery	Lead acid battery	Flow battery (vanadium)	Sodium sulfur battery	NiCd battery	Zinc-Bromine flow battery	Hydrogen Fuel Cells
1. Geographic limitations (GL)	L	L	H	H	H	H	H	H	H	H	H
2. Integration simplicity with renewable energy (IS)	L	L	H	H	H	H	M	H	H	M	M
3. Power flow balancing (PFB)											
Power fluctuation suppression (PFS)	L	L	H	H	H	H	M	M	M	M	L
Load following and ramping (LFR)	M	M	H	H	M	M	M	M	M	M	M
Spinning reserve (SPR)	L	M	M	L	M	M	M	M	M	M	M
Standing reserve (STR)	M	M	L	L	M	M	M	M	M	M	M
Voltage regulation and control (VRC)	L	L	M	M	M	M	M	M	M	M	L
Low voltage ride through (LVRT)	L	L	H	M	H	H	M	M	M	M	L
4. Power system reliability (PSR)											
Black-start (BS)	H	H	L	L	M	H	H	H	H	H	M
End-user service reliability (EUSR)	L	L	M	H	H	M	M	H	M	M	L
Uninterruptible power supply (UPS)	L	M	H	H	H	H	M	M	H	M	M
Transmission upgrade deferral (TUD)	H	M	L	L	H	M	M	M	H	M	M
Power quality (PQ)	L	L	H	H	H	H	M	M	M	M	M
Transmission and distribution stability (TDST)	L	L	H	M	H	M	M	M	M	M	M
5. Storage for later use (SLU)											
Seasonal storage (SS)	M	H	L	L	L	L	L	L	L	L	M
More power backup for later use (PB)	M	M	L	L	M	M	M	M	M	M	M
Peak shaving and load levelling (PSLL)	H	H	M	M	H	H	M	H	H	M	M
6. Toxic effects of storage technology (TE)	H	H	H	H	L	L	L	L	L	L	H

Note: H = Highly promising or experienced, **M** = Moderately promising, **L** = Least promising or infeasible

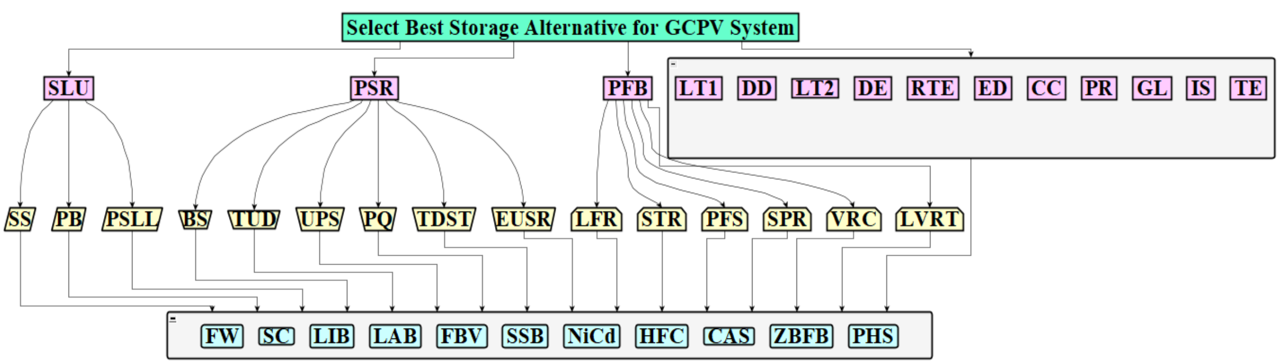


FIGURE 2. Hierarchy of the storage selection problem for GCPV system.

A. STEP 1. ORGANIZE THE PROBLEM INTO HIERARCHY LEVELS

The hierarchy of storage selection in this paper includes goal, level 1 criteria, level 2 criteria or sub-criteria, and alternatives. Goal of the storage selection problem was "Select Best Storage Alternative for GCPV System". Level-1 criteria include eight storage parameters and six qualitative compatibility criteria. Level-2 criteria or sub-criteria include

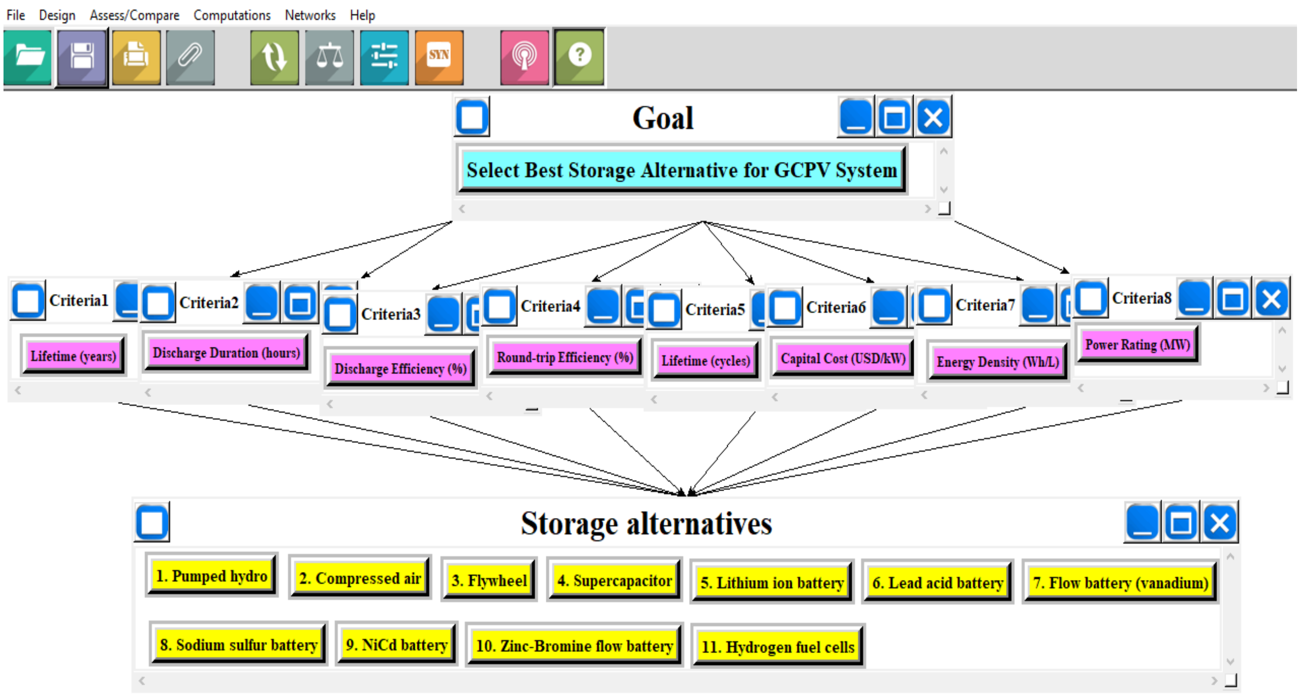


FIGURE 3. AHP model in super decisions using only eight quantitative storage criteria.

15 sub-criteria. Alternatives include 11 storage technologies presented in Table 1 and Table 2.

B. STEP 2. PERFORM PAIRWISE COMPARISONS

In this step, all the criteria, sub-criteria, and alternatives are compared pairwise in a logical way to develop pairwise comparison matrix. The elements within a particular hierarchy level are compared pairwise with respect to a specific element in the immediate upper level. In super decisions software, the quantitative factors were compared based on the numerical values in Matrix mode (Figure 7) and the qualitative factors were entered in the Questionnaire mode (Figure 8). To covert the qualitative judgment to the numerical values, the "1" represented the equally important and the "9" represented the extremely more important as specified in AHP method. In the present paper, Level-1 criteria were pairwise compared with respect to goal node. Also, the Level-2 criteria or sub-criteria were pairwise compared with respect to each linked criterion in the Level-1. Finally, alternatives were pairwise compared with respect to each criterion in Level-2 criteria or the Level-1 criteria whichever is directly attached with alternatives. The eigenvectors are calculated based on the comparison matrix.

C. STEP 3. PERFORM THE CONSISTENCY TEST

The inconsistency in the pairwise comparisons must be calculated. The maximum inconsistency is recommended as 10%. In the present model, inconsistency was considerably lower than 0.10 for each pairwise comparison. Finally, AHP method constructs the pairwise matrix and the ranking of alternatives is made. In AHP method, the consistency test identifies the errors in the judgement matrix. If the consistency ratio is more than 0.10, the pairwise comparisons must be revised trough the collection of the additional information about the judgements. Reference [99] includes a thorough description about the importance and implementation of the consistency test with reference to AHP method and the proposed software.

D. STEP 4. DETERMINE THE PRIORITIES OF ALTERNATIVES AND PERFORM SENSITIVITY ANALYSIS

In this step, the alternatives are ranked by aggregating the relative weights in the hierarchy. Finally, this paper performed the sensitivity analysis of the AHP model.

V. RESULTS AND DISCUSSION

This section evaluates the different storage technologies for GCPV systems using AHP method. The proposed AHP model offers the evaluation of the numerous cases. However, this paper presents the results for only the seven different cases.

A. CASE 1. ALL THE STORAGE PARAMETERS ARE EQUALLY PREFERABLE

In this case, only the eight quantitative storage parameters were included from Table 1 (Figure 3). In this case, the qualitative compatibility criteria were not included. In this case, all the eight quantitative storage parameters were given the equal priority for the pairwise comparisons between these parameters with respect to goal. The pairwise comparisons between all the 11 storage alternatives were derived from the real data in Table 1. For example, the pumped hydro storage has the life time of the maximum 60 years and the compressed air storage has the life time of the maximum 40 years. Here, the pumped hydro storage is 1.5 times more preferable than the compressed air storage. This comparison value was entered into super decisions software using Matrix mode (Figure 7).

Figure 4 presents the AHP model results obtained in the Super Decisions software based on the Case 1. In the Case 1, the pumped hydro storage obtained the first priority. The hydrogen storage received the second priority. It can be interpreted that the hydrogen storage is 67% as good as the pumped hydro storage. Similarly, the flywheel storage is 57% as good as the pumped hydro storage. In this case, the NiCd battery received the least priority. Also, all the batteries achieved inferior ranking compared with the remaining technologies. The pumped hydro storage gained the first priority, which suggests that this storage technology may face the overall less challenges compared with the other storage technologies.

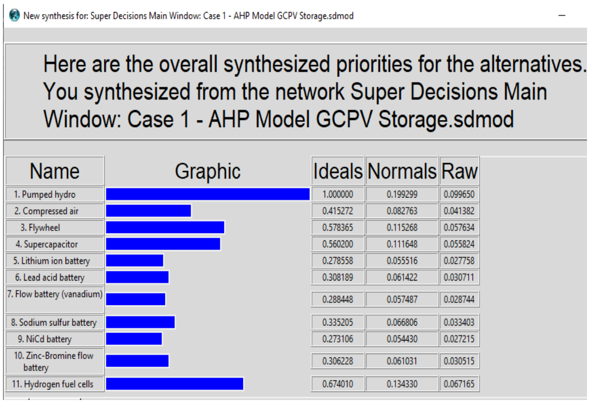


FIGURE 4. **Case 1. All the storage parameters are equally preferable.**

In Figure 4, column "Raw" is achieved from Limit Supermatrix in Super Decisions software. The columns "Normals" and "Ideals" are derived from the column "Raw" as explained in the literature [99]. The values in the Raw, Normals, and Ideals columns are computed within the Super Decisions software. The limit supermatrix is the final matrix which shows the preferences of each criteria. The values in column "Raw" are directly obtained from the limit supermatrix. It is somewhat difficult to interpret the results contained in column "Raw". Alternatively, column "Normals" and "Ideals" interpret the priorities more clearly than column "Raw". The values in the column "Normals" are normalized values obtained through dividing each value in column "Raw" by the sum of all the values in column "Raw". Sum of all the values in column "Normals" becomes equal to 1. Hence, column "Raw" shows the exact weight of each result. The column "Ideals" is obtained through dividing each value in column "Raw" by the largest value in column "Raw". In columns "Ideal", the best alternative shows the first priority. Hence, the values in the Raw, Normals, and Ideals columns are different ways of presenting the results of the model. In this paper, the interpretation of the results has been explained based on column "Ideals".

B. CASE 2. ALL THE STORAGE PARAMETERS AND COMPATIBILITY CRITERIA ARE EQUALLY PREFERABLE

In the Case 1, only eight quantitative storage criteria were included from Table 1. However, the compatibility criteria must be included for the more valid and rational decision making. From Case 2 to Case 6, the AHP model has been extended to include the qualitative factors related to the compatibility of the storage technologies with GCPV systems (Figure 5). In Figure 5, the eight quantitative storage criteria (i.e. Criteria1 to Criteria8) have been minimized at the upper left corner of the AHP model.

In the Case 2, the eight storage criteria and all the compatibility criteria were given the equal preferences in Super Decisions software. The priorities for all the 11 storage alternatives were derived from the real data from Table 1 and Table 2. In Super Decisions software, the pairwise comparisons between the qualitative factors (Table 2) with level "H" and level "M" were made as strongly (i.e. five times) more or less preferable, as per AHP method rules. Also, the pairwise comparisons between factors with level "H" and level "L" were made as extremely (i.e. nine times) more or less preferable. Similarly, the pairwise comparisons between factors with level "M" and level "L" were made as strongly (i.e. five times) more or less preferable. For instance, Figure 8 presents the Questionnaire mode for pairwise comparison between storage alternatives for sub-criteria "seasonal storage".

Figure 6 presents the AHP model results obtained in the Super Decisions software based on the Case 2. In the Case 2, the pumped hydro storage obtained the first priority. The rankings for remaining alternatives were same as in Case 1. However, the overall superiority of these remaining technologies increased with respect to pumped hydro storage, which can be observed by comparison of AHP results in Figure 4 and Figure 6.

C. CASE 3. CAPITAL COST IS EXTREMELY MORE PREFERABLE

In the Case 3, the Case 2 was modified in such a way that the criteria "capital cost" was considered the extremely more preferable than all other criteria with respect to goal. In Case 3, all the other quantitative and qualitative criteria, except "capital cost", were given the equal preferences in pairwise comparison with respect to goal. Figure 9 presents the AHP model results obtained in the Super Decisions software based on the Case 3. In the Case 3, flywheel storage gained the first ranking and the supercapacitor gained the second ranking. However, only flywheel and supercapacitor cannot accommodate the highly fluctuating PV power. In this case, the lead acid batteries and pumped hydro storage can be combined with flywheel or supercapacitor. Other batteries look expensive in addition to the low rankings based on other qualitative and quantitative criteria.

D. CASE 4. ENERGY DENSITY IS EXTREMELY MORE PREFERABLE

In the Case 4, the Case 2 was modified in such a way that the criteria "energy density" was assigned the extremely

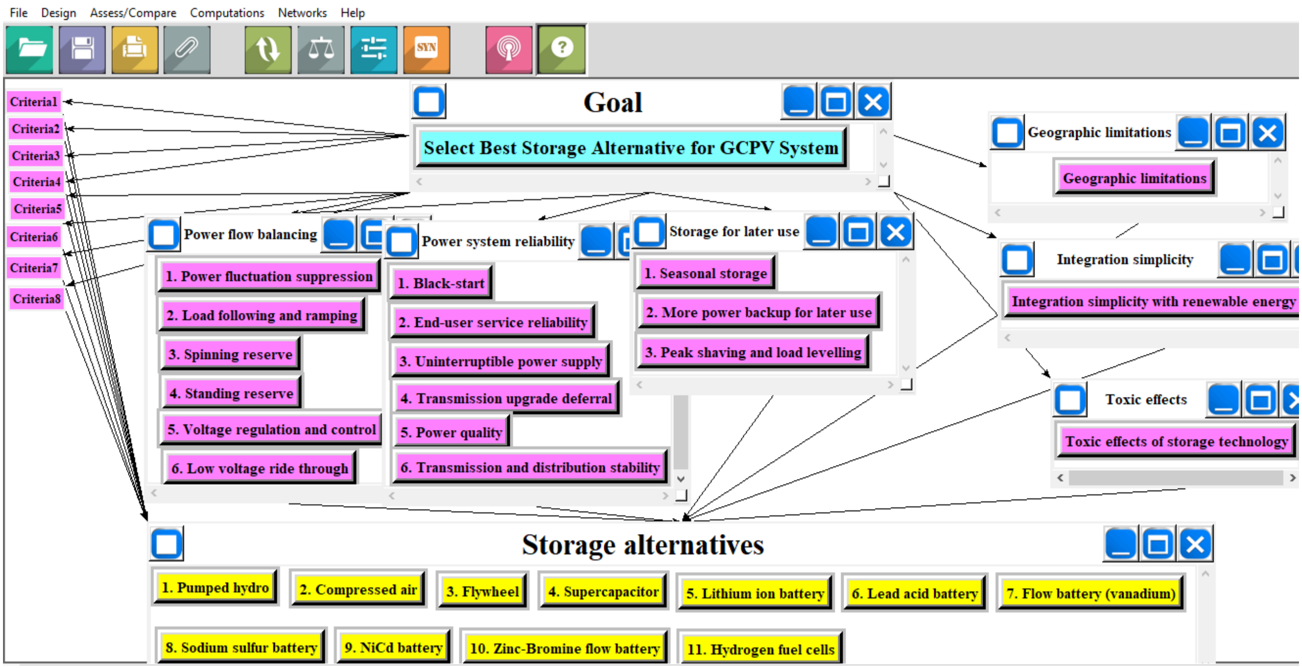
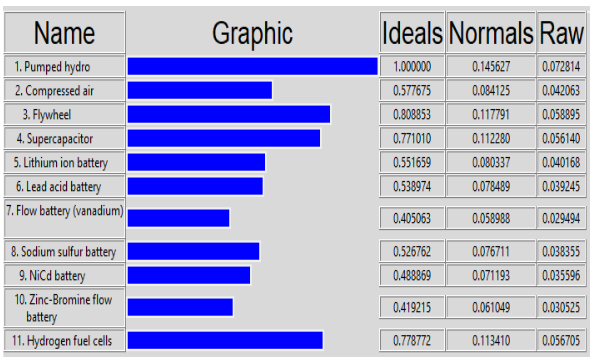


FIGURE 5. AHP model in super decisions using eight quantitative criteria and various qualitative criteria/sub-criteria.



Name	Graphic	Ideals	Normals	Raw
1. Pumped hydro		1.000000	0.145627	0.072814
2. Compressed air		0.577675	0.084125	0.042063
3. Flywheel		0.808853	0.117791	0.058895
4. Supercapacitor		0.771010	0.112280	0.056140
5. Lithium ion battery		0.551659	0.080337	0.040168
6. Lead acid battery		0.538974	0.078489	0.039245
7. Flow battery (vanadium)		0.405063	0.058988	0.029494
8. Sodium sulfur battery		0.526762	0.076711	0.038355
9. NiCd battery		0.488869	0.071193	0.035596
10. Zinc-Bromine flow battery		0.419215	0.061049	0.030525
11. Hydrogen fuel cells		0.778772	0.113410	0.056705

FIGURE 6. Case 2. All the storage parameters and qualitative compatibility criteria are equally preferable.

more preferable than all other criteria with respect to goal. In Case 4, all the other quantitative and qualitative criteria, except "energy density", were given the equal preferences in pairwise comparison with respect to goal. Figure 10 presents the AHP model results obtained in the Super Decisions software based on the Case 4. In the Case 4, hydrogen storage gained the first priority due to its highest energy density. Also, flywheel storage gained second priority and pumped hydro obtained third priority. It can be noted that the pumped hydro storage has very low energy density but it obtained third ranking even if we gave extreme importance to the energy density.

E. CASE 5. ENVIRONMENTAL SUSTAINABILITY IS EXTREMELY MORE PREFERABLE

In the Case 5, the Case 2 was modified in such a way that the priorities were set as follows.

- Three criteria "lifetime (in years), lifetime (in cycles), and the "toxic effects of storage technology" are extremely more preferable than all the other criteria in pairwise comparisons with respect to goal. These three criteria are equally important or preferable in pairwise comparisons with respect to goal.
- All the remaining quantitative and qualitative criteria have the equal preferences in the pairwise comparison with respect to goal.
- The alternatives are pairwise compared using real data in Table 1 and Table 2.

Figure 11 presents the AHP model results obtained in the Super Decisions software based on the Case 5. In the Case 5, the supercapacitor storage gained the first priority. However, pumped hydro and flywheel storage also gained the results very close to the supercapacitor. Batteries exhibited inferior rankings. It can be interpreted that the batteries seem worst storage technologies if the environmental sustainability criterion is given extreme preference on all the remaining criteria. The results from the Case 5 suggest that the combinations of pumped hydro, compressed air, flywheel, and supercapacitor may provide a sustainable alternative for the GCPV systems. However, pumped hydro and compressed air storage have the issues of integration difficulties and geographic limitations. Hence, Case 6 includes these criteria in the decision making.

F. CASE 6. GEOGRAPHIC LIMITATIONS AND INTEGRATION SIMPLICITY ARE EXTREMELY MORE PREFERABLE

In the Case 6, the Case 2 was modified in such a way that the criteria "integration simplicity regarding renewable energy" and "geographic limitations" were considered the extremely more preferable than all the other criteria with respect to goal.

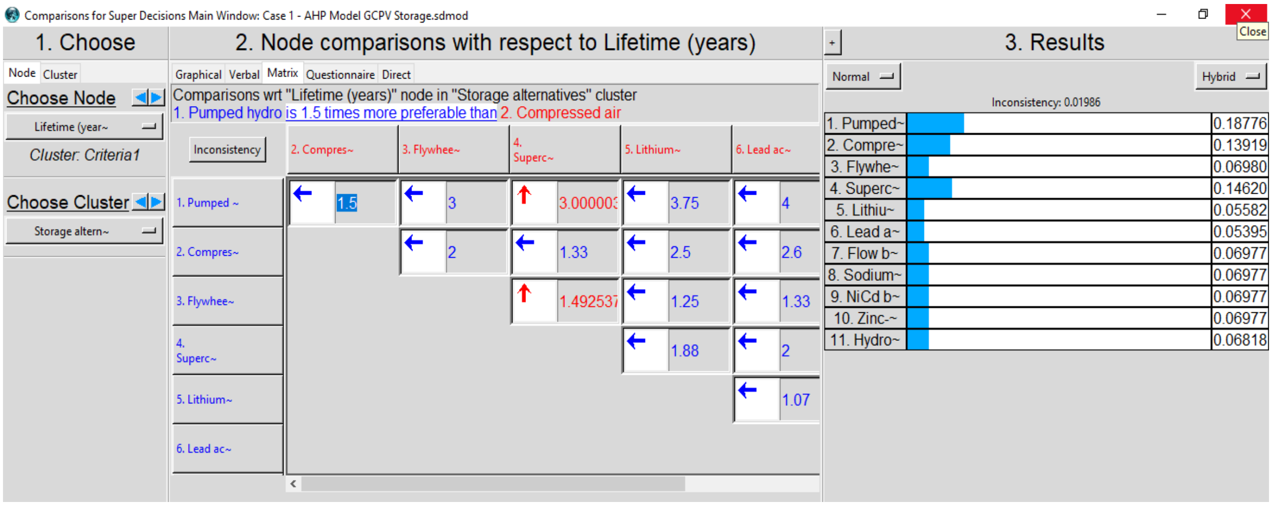


FIGURE 7. Super decisions software window displaying Matrix mode for pairwise comparisons and consistency results.

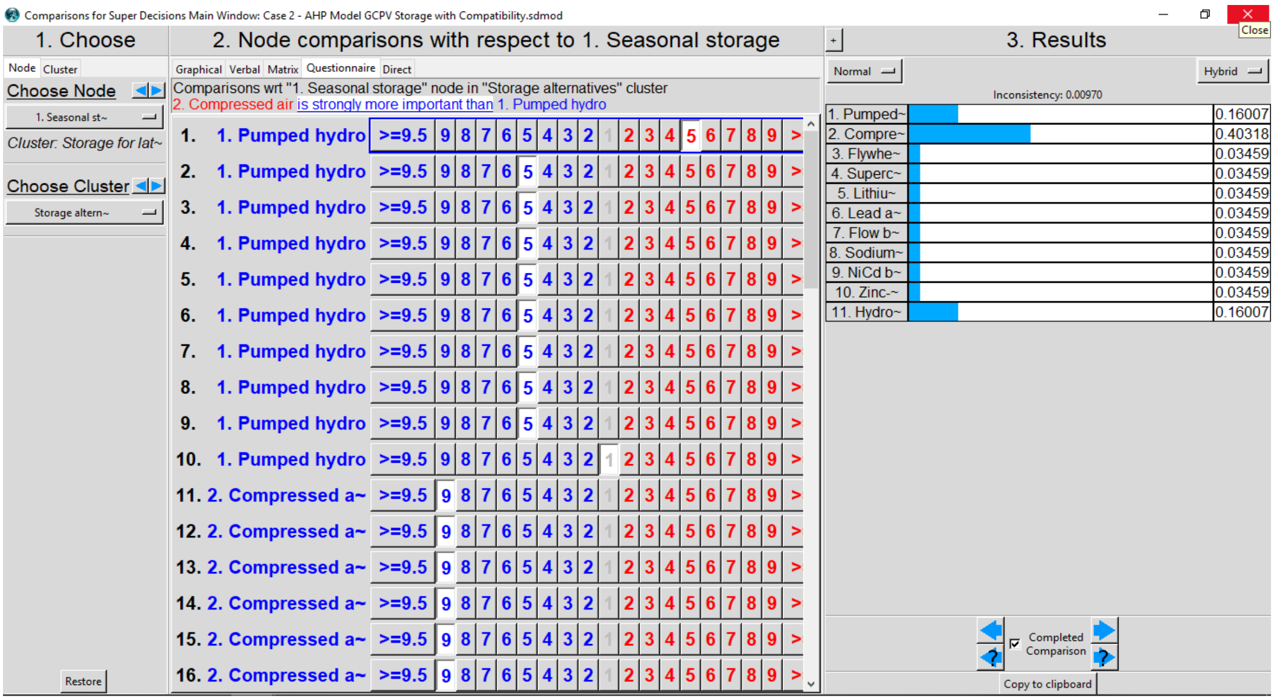
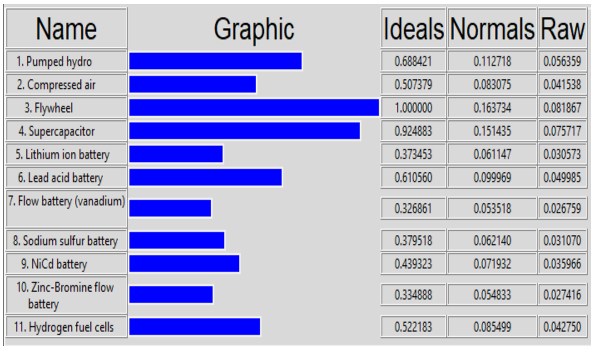


FIGURE 8. Super decisions software window displaying Questionnaire mode for pairwise comparisons.

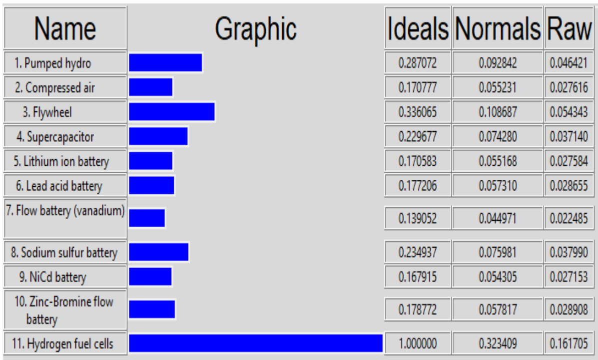
In the Case 6, the flywheel, supercapacitor, and most of the batteries obtained the higher rankings than the pumped hydro storage and compressed air storage (Figure 12). In the existing literature, the most of the GCPV models used the battery storage technologies. The ''integration simplicity regarding renewable energy'' and least ''geographic limitations'' may be a key reason for the frequent use of the battery technologies in the GCPV system. In addition, the availability of a range of batteries may be a reason of the frequent use of the battery technologies in the GCPV system.

It is evident that the battery storage systems will remain expensive in the coming decades. In order to increase the share of the renewable energy resources, there is a need to take the revolutionary steps such as the frequent integration of the other storage systems. For instance, the large scale pumped hydro storage are widely used technology in the world. The integration of the small and medium sized pumped hydro storage systems may revolutionize the grid-connected PV systems [103]. In addition, the literature has reported the effectiveness of the combination of different storage systems. For example, the flywheels and supercapacitors have been used with the battery technologies in the GCPV system. Moreover, the combination of battery storage with pumped hydro storage can decrease the electricity cost of the grid connected power systems [104].



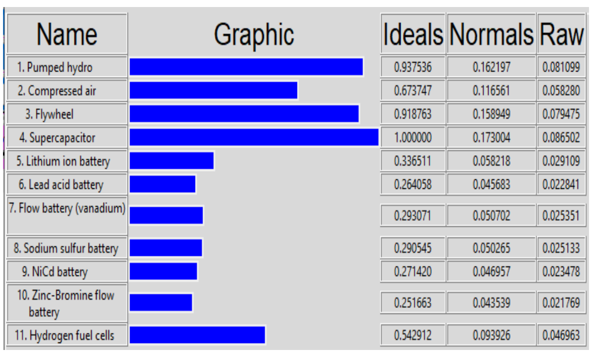
Name	Graphic	Ideals	Normals	Raw
1. Pumped hydro		0.688421	0.112718	0.056359
2. Compressed air		0.507379	0.083075	0.041538
3. Flywheel		1.000000	0.163734	0.081867
4. Supercapacitor		0.924883	0.151435	0.075717
5. Lithium ion battery		0.373453	0.061147	0.030573
6. Lead acid battery		0.610560	0.099969	0.049985
7. Flow battery (vanadium)		0.326861	0.053518	0.026759
8. Sodium sulfur battery		0.379518	0.062140	0.031070
9. NiCd battery		0.439323	0.071932	0.035966
10. Zinc-Bromine flow battery		0.334888	0.054833	0.027416
11. Hydrogen fuel cells		0.522183	0.085499	0.042750

FIGURE 9. Case 3. Capital cost is extremely more preferable.



Name	Graphic	Ideals	Normals	Raw
1. Pumped hydro		0.287072	0.092842	0.046421
2. Compressed air		0.170777	0.055231	0.027616
3. Flywheel		0.336065	0.108687	0.054343
4. Supercapacitor		0.229677	0.074280	0.037140
5. Lithium ion battery		0.170583	0.055168	0.027584
6. Lead acid battery		0.177206	0.057310	0.028655
7. Flow battery (vanadium)		0.139052	0.044971	0.022485
8. Sodium sulfur battery		0.234937	0.075981	0.037990
9. NiCd battery		0.167915	0.054305	0.027153
10. Zinc-Bromine flow battery		0.178772	0.057817	0.028908
11. Hydrogen fuel cells		1.000000	0.323409	0.161705

FIGURE 10. Case 4. Energy density is extremely more preferable.



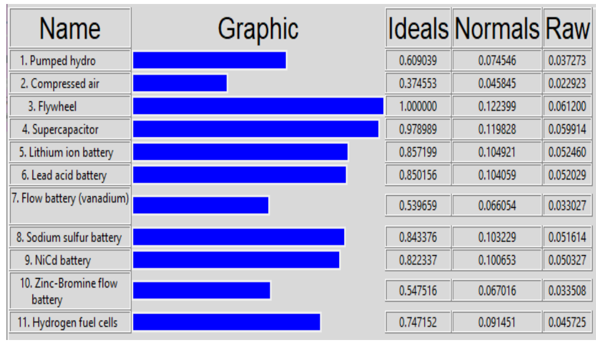
Name	Graphic	Ideals	Normals	Raw
1. Pumped hydro		0.937536	0.162197	0.081099
2. Compressed air		0.673747	0.116561	0.058280
3. Flywheel		0.918763	0.158949	0.079475
4. Supercapacitor		1.000000	0.173004	0.086502
5. Lithium ion battery		0.336511	0.058218	0.029109
6. Lead acid battery		0.264058	0.045683	0.022841
7. Flow battery (vanadium)		0.293071	0.050702	0.025351
8. Sodium sulfur battery		0.290545	0.050265	0.025133
9. NiCd battery		0.271420	0.046957	0.023478
10. Zinc-Bromine flow battery		0.251663	0.043539	0.021769
11. Hydrogen fuel cells		0.542912	0.093926	0.046963

FIGURE 11. Case 5. Environmental sustainability is extremely more preferable.

G. CASE 7. CRITERIA "POWER FLOW BALANCING", "POWER SYSTEM RELIABILITY", AND "STORAGE FOR LATER USE" ARE EXTREMELY MORE PREFERABLE

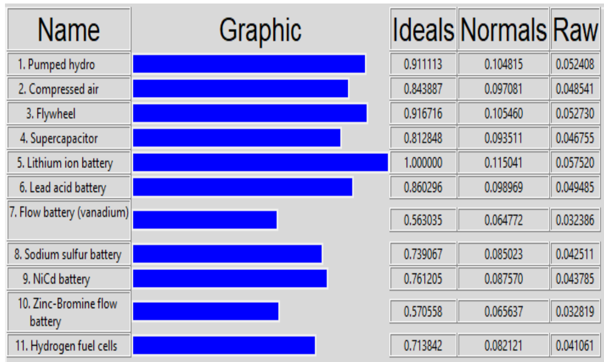
In the proposed hierarchy, the three criteria including ''power flow balancing'', ''power system reliability'', and ''storage for later use'' cover the most important sub-criteria which are the integral parts of a power system. These factors ensure the compatibility of a storage system with the grid connected power systems. In the Case 7, these three criteria have been given the extreme preference with respect to all the remaining criteria.

Figure 13 presents the results based on the Case 7. It can be observed that the lithium ion battery has obtained the first priority. The pumped hydro and flywheel storage obtained the next priorities. Then, the lead acid batteries exhibited the good ranking. The flow batteries and Zinc-Bromine flow batteries obtained the least preferences. Hence, lithium ion battery may be a competitive storage alternative for the grid connected power systems. However, if the decision maker wishes to include some other important criteria into decision making, the final ranking may change.



Name	Graphic	Ideals	Normals	Raw
1. Pumped hydro		0.609039	0.074546	0.037273
2. Compressed air		0.374553	0.045845	0.022923
3. Flywheel		1.000000	0.122399	0.061200
4. Supercapacitor		0.978989	0.119828	0.059914
5. Lithium ion battery		0.857199	0.104921	0.052460
6. Lead acid battery		0.850156	0.104059	0.052029
7. Flow battery (vanadium)		0.539659	0.066054	0.033027
8. Sodium sulfur battery		0.843376	0.103229	0.051614
9. NiCd battery		0.822337	0.100653	0.050327
10. Zinc-Bromine flow battery		0.547516	0.067016	0.033508
11. Hydrogen fuel cells		0.747152	0.091451	0.045725

FIGURE 12. Case 6. Geographic limitations and integration simplicity are extremely more preferable.



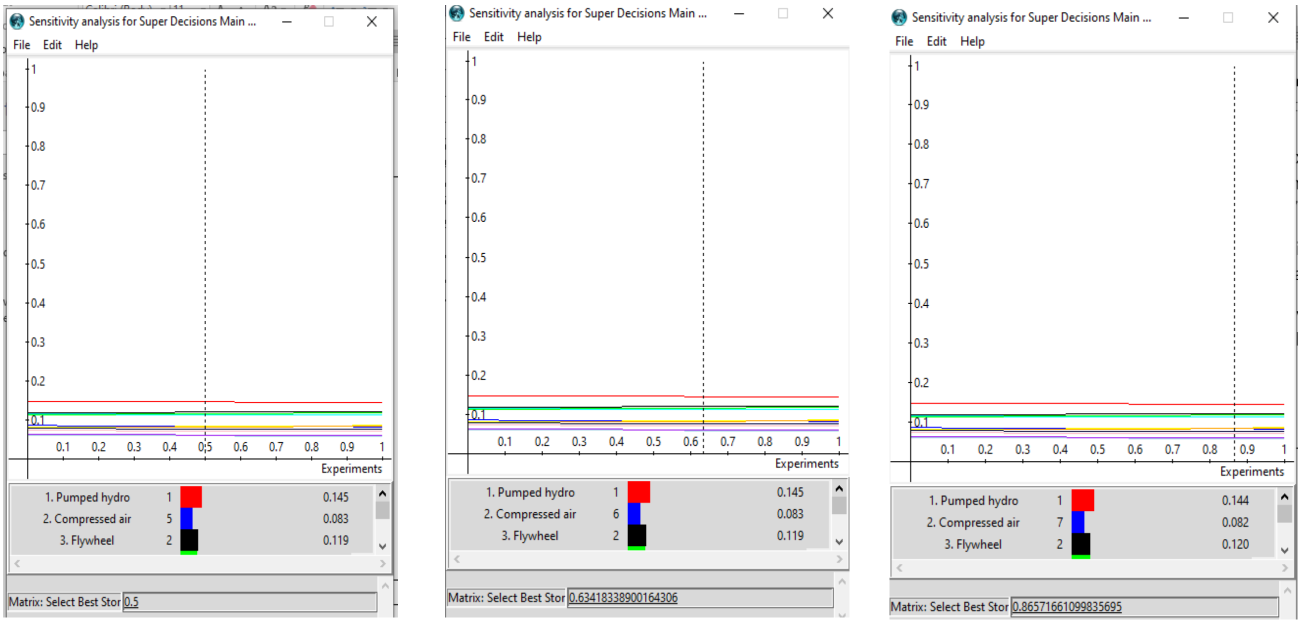
Name	Graphic	Ideals	Normals	Raw
1. Pumped hydro		0.911113	0.104815	0.052408
2. Compressed air		0.843887	0.097081	0.048541
3. Flywheel		0.916716	0.105460	0.052730
4. Supercapacitor		0.812848	0.093511	0.046755
5. Lithium ion battery		1.000000	0.115041	0.057520
6. Lead acid battery		0.860296	0.098969	0.049485
7. Flow battery (vanadium)		0.563035	0.064772	0.032386
8. Sodium sulfur battery		0.739067	0.085023	0.042511
9. NiCd battery		0.761205	0.087570	0.043785
10. Zinc-Bromine flow battery		0.570558	0.065637	0.032819
11. Hydrogen fuel cells		0.713842	0.082121	0.041061

FIGURE 13. Case 7. Criteria "power flow balancing", "power system reliability", and "storage for later use" are extremely more preferable.

VI. SENSITIVITY ANALYSIS

This paper tests the validity and robustness of the results through the sensitivity analysis. In AHP method, sensitivity analysis studies the effects of criteria changes on the alternative solutions. Super decisions software provides the sensitivity analysis feature. In this feature, the sensitivity analysis evaluates the effect of changes in the weights of the criteria on the results. The weight of the criteria represents the priority of criteria. This paper performed sensitivity analysis of AHP model by changing the weights of criteria and sub-criteria.

The sensitivity analysis exhibited that the large input variations in weights of criteria did not affect the final decision. We consider the level-1 criteria in the Case 2 in which sensitivity analysis exhibited no change in the final decision about storage selection. However, a few qualitative factors with very close values of output changed the priority. Also, the level-2 criteria did not exhibit the change in the final decision based on the input variations. For instance, the priority of the criteria ''power fluctuation suppression'' is presented on x-axis and the priority of alternatives is presented on y-axis in Figure 14.



50% priority of criteria **63% priority of criteria** **86% priority of criteria**

FIGURE 14. Sensitivity analysis for criteria "Power fluctuation suppression" with respect to alternatives.

Vertical line is used to set the priority of criteria. First, the criteria "power fluctuation suppression" was given the 50% priority. Then, the priority was gradually increased to 60%, 70%, 80%, 90%, and 100%. In all cases, the pumped hydro storage remained the final selection. However, at 63% priority of "power fluctuation suppression" the priority of compressed air storage changed from 5th ranking to 6th ranking. In this case, lithium ion battery achieved the 5th ranking. Gradually increasing the priority of "power fluctuation suppression" to 86%, the priority of compressed air storage changed to 7th ranking. In this case, lithium ion battery achieved the 5th ranking and the lead acid battery occupied the 6th ranking. This ranking did not alter until 100% priority of "power fluctuation suppression". Hence, the lithium ion battery may be preferable on the compressed air storage. This change of rankings was due to the fact that the compressed air storage, lithium ion battery, and lead acid battery obtained very close values of results. However, this trend was observed for a few criteria in which alternative results are very close to each other. For most of the criteria, the results remained very stable. Therefore, it can be concluded that the results are very stable and robust.

VII. CONCLUSION AND FUTURE RESEARCH

This paper presents a storage selection method based on the analytic hierarchy process (AHP) approach for the grid-connected photovoltaics (GCPV) systems. The AHP model incorporates the eight quantitative criteria related to the primary characteristics of storage and the various qualitative criteria related to the compatibility with GCPV systems. The results provide various insights based on the secondary data used in this paper.

When the AHP model included only the eight quantitative storage criteria and these criteria were assigned the equal preference, the pumped hydro storage received the first priority and the hydrogen storage received the second priority. In this case, batteries offer a poor alternative (Case 1). In the next trials, the AHP model included the eight quantitative storage criteria as well as all the qualitative compatibility criteria (Case 2 to Case 6). In these trials, if all the quantitative and qualitative criteria were given the equal preference, the pumped hydro storage received the first priority (Case 2). However, the performance of the remaining technologies improved. In the next trial, the criteria "capital cost" was given extreme preference in pairwise comparison with other criteria with respect to goal (Case 3). In this case, it can be suggested that the combinations of flywheel and supercapacitor with lead acid batteries and pumped hydro storage seem economic. However, the remaining batteries obtained worst rankings. In the next trial, the criteria "energy density" was given the extreme preference in the pairwise comparison with other criteria with respect to goal (Case 4). In this case, hydrogen storage gained the first priority. Then, the next trial included the environmental sustainability into AHP model (Case 5). In this case, the supercapacitor, pumped hydro, and flywheel storage gained the good rankings.

In the Case 5, the batteries exhibited the inferior rankings. It can be interpreted that the batteries seem worst storage technologies if the environmental sustainability criterion is given extreme preference on all the remaining criteria. The results from this case suggest that the combinations of pumped hydro, compressed air, flywheel, and supercapacitor may provide a sustainable alternative for the GCPV systems. In the next trial (Case 6), the "integration simplicity regarding renewable energy'' and ''geographic limitations'' were extremely preferred with respect to goal. In this case, many storage technologies gained the ranking better than the pumped hydro and compressed air. In this case, most of the batteries obtained good results. In Case 7, criteria ''power flow balancing'', ''power system reliability'', and ''storage for later use'' were given highest preference on the other criteria. In this case, the lithium ion battery obtained the highest ranking. These results confirm the findings of the existing literature in which the battery storage has been used frequently in the GCPV systems. The pumped hydro storage and compressed air may not be frequently used in GCPV systems due to the lower geographic limitation and less integration simplicity. The flywheel and supercapacitor storage obtained an excellent rank for the integration into GCPV system. However, the flywheel and supercapacitor storage offer a short term solution for the power fluctuations. The flywheel storage and supercapacitor can be used with other storage technologies to increase the effectiveness of storage system. However, the literature concludes that the integration of battery storage technologies is a costly option. Therefore, this paper suggests the extensive research on the integration of the alternative storage technologies, such as pumped hydro, compressed air, and hydrogen, in the GCPV systems.

The proposed AHP model offers the flexibility to evaluate the storage technologies for the grid-connected power systems under numerous circumstances. For instance, future research may give the different priorities to the certain primary storage characteristics based on the requirements. Also, the qualitative criteria related to the compatibility can be modified based on the grid types such as microgrid, super grid, and any other power network. This paper performs the decision making based on 11 quantitative criteria, six qualitative factors/criteria, and 15 qualitative sub-criteria. Future research may use many other criteria and sub-criteria into AHP model according to the requirements. The increase or change of qualitative factors will change the decision making outcomes. Future research may combine different storage technologies in AHP model for the storage system selection. This paper included only those storage technologies that have been addressed in the existing literature related to GCPV systems. Future research may include other important storage technologies, such as power-to-gas storage (P2G).

In AHP method, the eigenvalue method is used to calculate the priorities of the alternatives. The eigenvectors obtained from the pairwise comparison metrics are not the Pareto optimal. However, AHP provides a good approximation for the decision making. Future research may modify the traditional AHP method to test the Pareto optimality of the solution obtained in the proposed storage selection model [105].

Future work may study the multi-criteria storage selection decisions in different ways such as utilization of other possible software/methods, integration of other optimization methods into AHP, and evaluation of other MCDM methods.

The proposed model has not been specified for a specific size of PV system. Future work may develop several models for each size and type of PV system. For this purpose, the most important parameters can be identified related to the compatibility of the storage systems with the required PV system. The different PV systems may have some differences in the storage system requirements. For example, the large scale PV system requires a large storage capacity. In this case, the storage capacity will be incorporated into the selection criteria and the storage capacity will be given the more preference in the model. Similarly, there may be many other parameters which should be included into the model depending on the size and type of PV systems.

This method can be adopted for other intermittent renewable energy based power systems such as grid connected wind power systems. For the identification of the storage parameters, this paper focused on the literature related to the grid-connected PV systems. Future work may perform a comprehensive review of the grid connected wind power systems in order to identify some additional parameters or factors related to wind storage systems. However, the qualitative factors used in the present paper can be used for the evaluation of other renewable energy based systems with fluctuating nature (e.g. wind power). Future work may perform the evaluation of the different storage systems for the different power systems considering the different renewable energy resources including wind power, wave power, and tidal power.

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