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Hybrid Multi-Criteria Decision Framework for Prosumers Energy Storage Systems in Smart Grids

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ABSTRACT Modern power systems encompass multiple prosumers, smart grid technologies, and renewable energy resources (RERs). These prosumer-based smart grids are facing the reliability issues that can be mitigated through the adoption of competitive storage technologies. A range of competitive storage technologies have been developed by scientists. However, the systematic selection of best storage technologies is still one of the main challenging research issues in the current literature. To fill this literature gap, this paper proposes a multi-criteria decision framework for energy storage selection in prosumer-based networks. First, a decision-making hierarchy was developed based on the three main criteria including energy flow management for prosumers, technical features, and sustainability. Under these criteria, various sub-criteria were identified. Second, multi-criteria decision making (MCDM) problem was solved for two cases using Analytic Hierarchy Process (AHP) and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) methods separately. Third, a hybrid AHP and PROMETHEE method was proposed for the selection of an efficient storage system for prosumers based smart grid. Finally, a comprehensive outlook has been provided for prosumer energy storage. The hybridization of AHP and PROMETHEE methods offered a more robust and unique solution to the storage selection problem as compared to existing literature.

INDEX TERMS AHP, energy management, multi-criteria methods, PROMETHEE, prosumer, renewable energy, smart grid.

I. INTRODUCTION

Prosumers in nano grids represent an integral part of modern smart grids [1]. Similarly, energy storage systems represent an integral part of prosumers [2]. A range of competitive energy storage systems are available, and the storage selection is a challenging problem for prosumers [3]. Usually, management decisions become inefficient and ineffective by improper selection of different resources [4]. In the same way, prosumer based smart grid becomes incompetent due to improper energy storage systems. Storage selection problems are challenging due to the consideration of multiple criteria such as cost, technical features, compatibility, social aspects, and environmental aspects [5-6]. The best way to solve multi-criteria problems is the use of multi-criteria decision making (MCDM) methods in operations research. Mostly used MCDM methods include AHP (Analytic Hierarchy Process), PROMETHEE (Preference Ranking Organization Method for Enrichment of Evaluations), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), multi-objective optimization, fuzzy AHP, fuzzy TOPSIS, weighted sum method, ELECTRE (Elimination and Choice Translating Reality), weighted product method, and VIKOR (Visekriterijumsko Kompromisno Rangiranje). It has been argued that no MCDM method is better than the other due to advantages and disadvantages of every method [7].

Decision maker can use any MCDM method in operations research. Also, decision makers can obtain more robust solution through the use of more than one method. First, this paper applied the AHP method for prosumers energy storage selection. AHP is a leading MCDM method that has been used to solve hundreds of sensitive MCDM problems [8]. Any other MCDM method can be used for the validation of AHP solution. In this regard, this paper selected PROMETHEE method which is also a prominent MCDM method in the decision sciences [9]. Hence, prosumer-based energy storage selection problem was validated by two different methods. However, the result might be slightly different for the two methods. In order to reach a unique conclusion, decision maker will need a hybrid MCDM storage selection method which should result in a unique, robust, and more reliable solution. Hence, this paper proposed a novel storage selection method based on hybrid AHP and PROMETHEE method.

In the following subsections, we present the storage need, storage benefits, storage alternatives, storage selection criteria, significance of MCDM methods, significance of hybrid AHP and PROMETHEE methods, research novelty, and objectives focusing on prosumers storage evaluation.

A. ENERGY STORAGE NEED FOR PROSUMERS

Futuristic power systems will facilitate the integration of multiple prosumers, multiple renewable energy resources, and a range of smart grids technologies [10]. A large number of electricity consumers will turn into prosumers (i.e. consumers as well as producers) due to fossil fuels shortage, expensive electricity, and access to substantial clean energy [11]. Ultimately, Sustainable Development Goal-7 of the United Nations (i.e. affordable and clean energy) would be supported for P2P energy networks [12]. However, the emergence of multiple prosumers would cause severe variability, instability, and demand variations in smart grids [13]. For example, the higher amounts of photovoltaics (PV) integration would result in overvoltage and overloading [14]. A competitive strategy to resolve such problems is the integration of competitive storage technologies into these challenging power systems [15].

B. STORAGE BENEFITS FOR PROSUMERS

Many studies reported the effectiveness of different storage technologies for the prosumer-based smart grids [16-17]. Many papers reported the cost savings for these systems. For instance, Reference [18] reported 35% cost savings for a grid-connected university campus using PV system, diesel generator, and battery. Also, Reference [19] reported significant cost savings for a system with residential prosumer, commercial prosumer, and pumped hydro storage system. Similarly, Reference [20] developed an optimal power sharing model for grid-connected residential and commercial prosumers with PV systems and battery storage. The proposed system offered 69% cost saving for a residential prosumer and 81% cost saving for a commercial prosumer. Many other papers have reported the cost savings from the prosumer-based smart grids with storage [21-23].
In addition to the cost savings, many papers reported the significant self-consumption for the storage systems under different settings. For example, Reference [24] performed techno-economic analysis of PV system with shared storage for a prosumer community. As a result, the self-consumption of the prosumer community was increased up to 11%. Also, Reference [25] optimized a prosumer-based power system using PV system with heat pump, batteries, and heat storage. It was concluded that the batteries and heat storage significantly increased the self-consumption of the prosumers. Similarly, Reference [26] used thermal energy storage for the storage of excess PV power in the form of heat in a prosumer-based power system. It was reported that the PV self-consumption and the renewable energy integration were increased. Also, the different storage systems have been integrated with the prosumers with the help of electric vehicles [27]. Reference [28] reported the use of power to gas technology for the storage of excess PV in the form of gas for the peer-to-peer prosumers. It was reported that the use of power to gas technology would decrease the reliance on the main grid. Further, Reference [29] analyzed the hydrogen storage with PV systems for the grid-connected residential prosumers and identified that the hydrogen storage is the only feasible option if power demand is high or highly seasonal, or the system operates in off-grid mode. Also, Reference [30] used hybrid battery and supercapacitor storage for a residential PV prosumer.

C. RECOMMENDED STORAGE SYSTEMS FOR PROSUMERS

Recently, most of the literature reported the use of batteries for the prosumer-based smart grids. However, many studies have reported the effectiveness of the other storage options. It can be concluded that a range of storage technologies would be integrated into the prosumer-based smart grids, such as batteries, pumped hydro storage, superconducting magnetic energy storage, flywheel energy storage, supercapacitors [31], solar thermal storage [32], hydrogen fuel cells [33], and compressed air energy storage [34]. Hence, this paper included these storage technologies into the multi-criteria decision making (MCDM) models.

D. STORAGE SELECTION CRITERIA FOR PROSUMERS

Most of the studies have recommended storage technologies for prosumers only on the basis of cost criteria. In fact, a storage technology should be judged based on all the important criteria related to the prosumer-based smart grids, specifically the criteria related to the technical characteristics, compatibility with prosumers, and the achievement of the sustainable development goals [35]. In this context, this paper integrates these main criteria into the storage selection decision making process. More specifically, this paper integrates three main criteria including the energy flow management for prosumers, technical features, and sustainability. Under these criteria, the many relevant sub-criteria have been identified in this paper. Besides, the storage selection is a MCDM problem that should be solved through the MCDM methods.

E. SIGNIFICANCE OF MCDM METHODS FOR PROSUMERS STORAGE SELECTION

Decision making methods in operations research and management sciences are greatly regarded by practitioners for very sensitive decision making. Amongst these methods, MCDM methods are considered more suitable for complex problems with multiple criteria and many alternatives. The exact optimization methods do not offer the integration of all the possible criteria or objectives, and they do not offer efficient solutions to such problems. In contrast, MCDM methods are very comprehensive and simple for efficient solution to a complex problem. There are many well established and proven MCDM methods. Each of these methods needs different information and work on different mathematical models. There is a possibility that different MCDM methods would offer different solutions. Comparison and combination of more than one MCDM method would offer more in-depth insights into the application problem as well as behavior of MCDM methods [36]. Hence, this paper performs the storage selection for prosumers in smart grids using two different MCDM methods, namely Analytic Hierarchy Process (AHP) and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE). AHP and PROMETHEE methods have been used in numerous MCDM problems for sensitive decision making [37-39]. The proposed storage selection problem contains the qualitative and quantitative criteria, and the proposed MCDM methods support the inclusion of both types of criteria.

F. SIGNIFICANCE OF HYBRID AHP AND PROMETHEE METHODS

Some papers combined the AHP and PROMETHEE methods for different problems. For instance, Reference [40] used hybrid AHP-PROMETHEE for the service provider selection for the hair care manufacturing company. They calculated criteria weights with AHP and used the PROMETHEE method for the ranking of alternative service providers. Similarly, Reference [41] evaluated the resilience of the four blocks in some drainage areas using hybrid AHP-PROMETHEE. They calculated the criteria weights from AHP and used them in the PROMETHEE for the ranking of four blocks. Reference [42] used hybrid AHP-PROMETHEE for the selection of fruit crops. They obtained criteria weights from AHP and used them in PROMETHEE for the ranking of fruit crops. These recent papers used hybrid AHP-PROMETHEE method in such a way that AHP was used for the finding of criteria weights and the PROMETHEE was used to rank the different types of alternatives. The above papers do not validate the results with a comparative selection method. In the present paper, the PROMETHEE method was applied using the weights from AHP method. Additionally, AHP was also used for the ranking of storage systems. Hence, this paper compares the storage alternatives from both methods. In addition, the present paper reports a novel procedure for the storage selection based on the hybrid solution from both methods, which further increases the reliability of the results.

Until now, the existing literature has not reported a systematic storage selection model for prosumers in smart grids. Majority of papers have focused only on the cost saving criteria. Furthermore, the storage selection literature on prosumers did not use scientifically established decision-making methods. For instance, Reference [34] compared lead acid, lithium ion, and redox flow batteries for the prosumer-based microgrids. It was found that the lead acid batteries would be least preferable for the small-scale prosumer-based microgrids. However, that comparison was based on the literature review of the different storage technologies. In contrast, the present paper includes all the relevant criteria and storage alternatives in the decision-making models. In addition, this paper performs the storage selection for prosumers in smart grids using the two leading MCDM methods, namely AHP and PROMETHEE. These methods have not been used for prosumers storage selection. However, a few comprehensive research used the AHP method for the storage selection in different applications. For instance, Reference [43] developed a storage selection model for grid-connected PV systems using AHP method. Also, Reference [44] applied AHP model for the storage selection for electric vehicles. However, these two papers focused only on the PV systems or electric vehicles. Furthermore, PROMETHEE was not used in these problems. Also, the present study includes the effect of prosumers in the storage selection problem.

G. NOVELTY AND OBJECTIVES

Prosumer based large scale power systems will emerge in the near future, and substantial storage capacity will be required in order to prevent the failure of the whole power system. Some batteries are toxic (e.g. lead-acid) and some batteries will face materials scarcity (e.g. lithium-ion). This will cause the integration of alternative batteries or other storage systems. In such situation, the storage selection and ranking will be a significant trend in these futuristic power systems. Prosumers will use all the required criteria in the storage selection problems, and the MCDM methods are the best candidates for multi-criteria selection and ranking problems. Hence, the problem and the proposed methods of this research are significant as well as sufficiently novel.

AHP and PROMETHEE combination is highly regarded in the literature. In this regard, weights are obtained from AHP, and the final ranking is achieved by PROMETHEE method. Although, this paper used a similar approach for PROMETHEE solution, the separate AHP solution has also been used for the final ranking. In addition, a novel hybrid method has been proposed using AHP and PROMETHEE solutions. Moreover, the integration of prosumers is an additional novelty which has not been achieved in literature. In the existing literature, some papers have used fuzzy set theory. For instance, Reference [45] applied fuzzy logic and AHP method for storage selection amongst flywheel, supercapacitors, pumped hydro, compressed air, and hydrogen storage alternatives. In that work, the individual application of fuzzy logic and AHP method resulted in exactly the same ranking. This shows the authenticity of AHP results. However, the integration of fuzzy set theory is suggested as more reliable, but still no work has proposed the storage selection model for prosumers using hybrid MCDM and fuzzy sets. We leave this investigation for future research and focus on the AHP and PROMETHEE methods. Still, no research has proposed the storage selection and ranking model using hybrid AHP and PROMETHEE methods. Even the separate application of these two methods has not been reported in the literature for prosumer-based storage systems. In contrast, this work reports hybrid application as well as separate application of both methods. Based on the research gap, this paper has the following key objectives.

- Identification of the criteria, sub-criteria, and alternatives for the MCDM problem focusing on the storage selection for prosumers in smart grids.
- Solution of the storage selection problem using hybrid AHP and PROMETHEE methods.
- Application of a novel storage selection procedure based on hybrid AHP and PROMETHEE methods.
- Establishment of a future outlook for proposed prosumers-based storage selection problem.

II. METHODOLOGY

This section proposes a systematic storage selection methodology for the prosumers in smart grids. This methodology has been presented in Figure 1. The proposed methodology contains 10 steps which have been explained in the following.

A. IDENTIFICATION OF STORAGE SELECTION CRITERIA

In the first step, storage selection criteria were identified for prosumer-based smart grids as shown in Figure 2. There are three main criteria including the energy flow management for prosumers, technical features, and sustainability.

First criterion "energy flow management for prosumers" is a central element of the energy management in prosumer-based smart grids. Under this criterion, there are four sub-criteria at level 1 and 14 sub-criteria at level 2. A brief description of these fourteen sub-criteria is given below.

1) SUPPORT IN BIDIRECTIONAL ENERGY SHARING (BISH)

Bidirectional energy sharing capability is the most important feature of the future smart grids, and prosumers are the key elements of such smart grids. A prosumer-friendly storage system should support the efficient bidirectional power flow [46]. Hence, the bidirectional energy sharing capability is an integral part of the storage selection criteria for the prosumer-based smart grids.

2) TRANSMISSION STABILITY AND CONGESTION MANAGEMENT (TRCON)

This criterion ensures the efficient operations of the transmission line parameters, resulting in congestion reduction and good power quality. The integration of multiple renewable energy resources, prosumers, and smart grid requires the effective strategies for the transmission stability and congestion management. For this purpose, the integration of a competitive storage system is a key supportive strategy.

3) TELECOMMUNICATIONS BACKUP (TELB)

Smart grids require a highly reliable and efficient communication flow. The prosumers would store the back-up power for the telecommunications in smart grids. For this purpose, a compatible storage system would supply reliable back-up power when required.

4) FLUCTUATION SUPPRESSION (FSUP)

This criterion ensures the mitigation of the fluctuations due to the renewable energy-based prosumers. The prosumer-based smart grids require the energy storage for the fluctuation suppression [47].

5) VARIABILITY REDUCTION (VRED)

The variability reduction is a key requirement of the renewable energy based smart grids, and prosumers are the key consumers and producers of the multiple renewable energy-based resources. A storage system should be capable of variability reduction for the prosumer-based power systems [48].

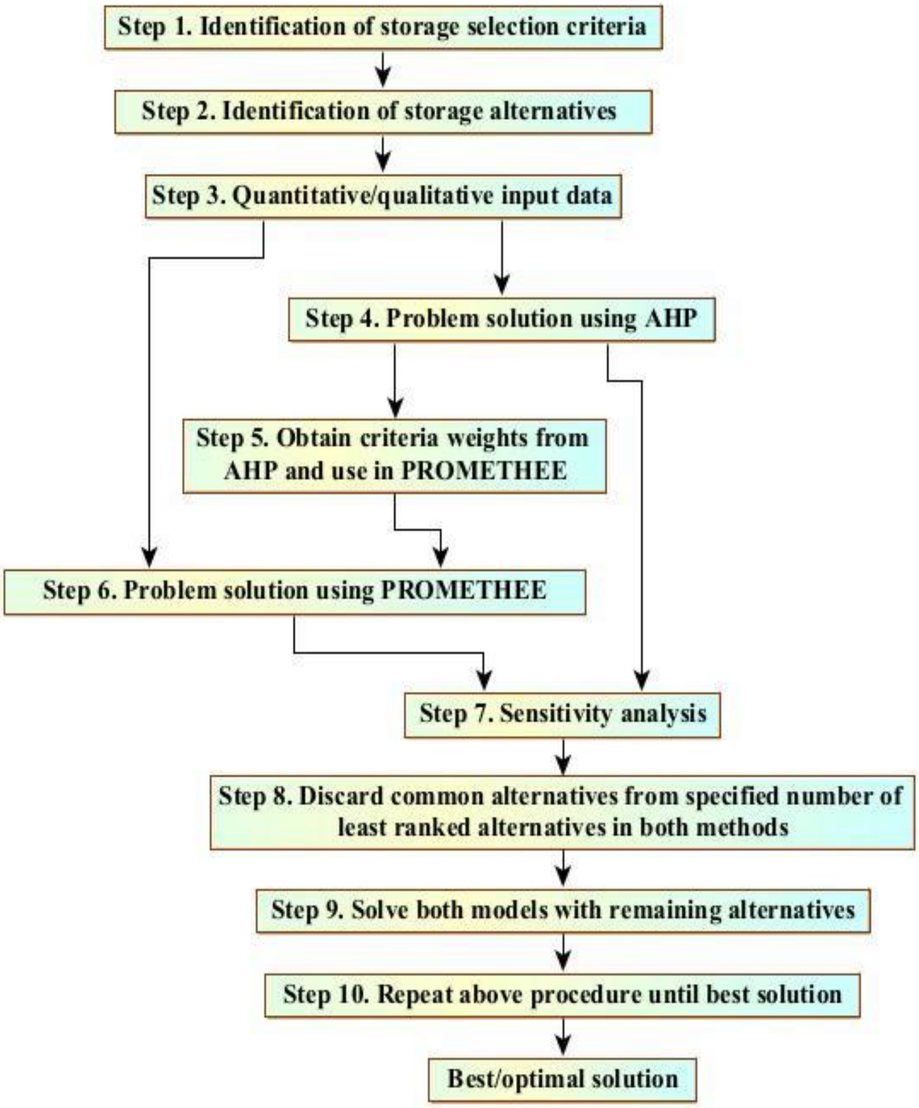


Figure 1. Storage selection methodology

6) TIME SHIFTING (TSHI)

Prosumers store the energy during the low prices or over-production and use it during the high prices or under-production. A storage system should be responsive during these times. Especially, the environmentally responsible prosumers would implement the time-shifting strategy according to their own production and the requirements of the utility grid [49].

7) PEAK SHAVING (PSHA)

Peak shaving allows a prosumer to store the energy during the peak times and use it during the off-peak times. According to this criterion, a good storage system should be able to store the power during peak generation [50]. Peak shaving would become an integral part of the prosumer-based smart grids [51].

8) LOAD LEVELLING (LLEV)

This feature ensures that a good storage system should store energy during the low demand and use it during the peak loads. Usually, the prosumers fulfill a major part of the demand from the renewable energy or utility grid. Sometimes, the renewable energy resource or the utility grid may not fulfill the demand. In such situations, the storage system should manage the large load variations.

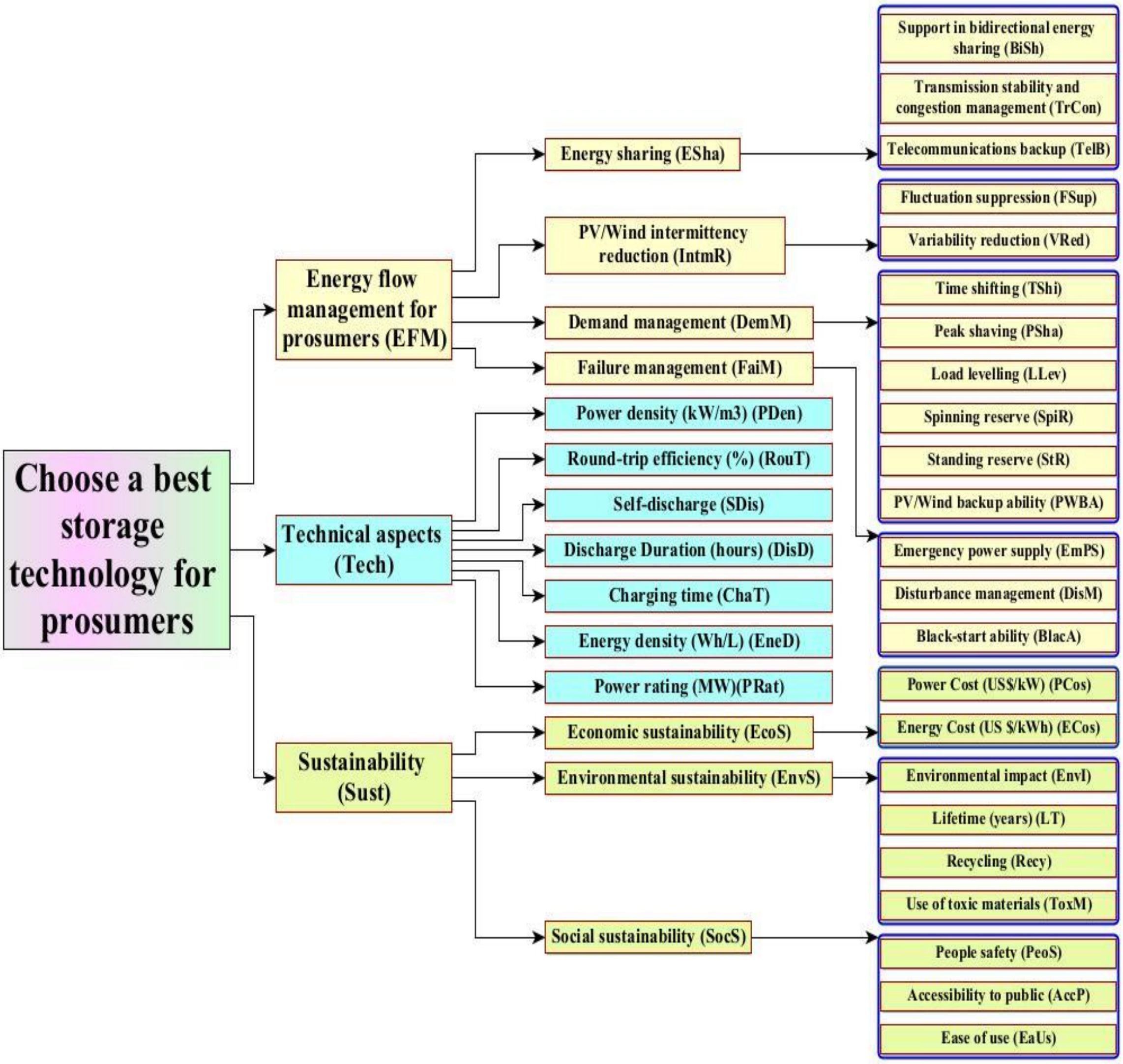


Figure 2. Storage selection criteria for prosumers in smart grids

9) SPINNING RESERVE (SPIR)

Prosumers would face a sudden increase in production during the peak generation hours or the power demand from utility grid or local loads may decrease. In such situations, a storage system should offer the quick spinning reserve.

10) STANDING RESERVE (STR)

Sometimes, a prosumer may lose the generation capacity or grid connection. In such situations, a storage system would work as a power generation unit.

11) PV/WIND BACKUP ABILITY (PWBA)

This criterion ensures that storage technology should be able to store energy for the times when the wind is not flowing or the sun is not shining, especially during the night times or the absence of sun or wind for the longer times.

12) EMERGENCY POWER SUPPLY (EMPS)

A storage system should be able to supply the power during failures.

13) DISTURBANCE MANAGEMENT (DISM)

A storage system should be capable to manage a disturbance (e.g. short circuit) in the power system.

14) BLACK-START ABILITY (BLACA)

This criterion ensures that a storage system should be able to reconnect the components of the power system after a blackout.

The second main criterion "technical features" contains the fundamental characteristics of a storage system. The third main criterion "sustainability" contains the three pillars of sustainability which should be integrated into the storage selection criteria due to their strong support towards the achievement of sustainable development goals. Hence, storage selection criteria of this paper include prosumer-related criteria, fundamental features, and criteria related to sustainable development.

Figure 3. Storage alternative for prosumers

B. IDENTIFICATION OF STORAGE ALTERNATIVES

In this step, the fifteen most important storage alternatives were identified based on the existing literature. These alternatives have been presented in Figure 3.

C. QUANTITATIVE/QUALITATIVE INPUT DATA

In this step, the qualitative and quantitative input data was collected (Table 1). The abbreviations for all the criteria have been presented in Figure 2, and the abbreviations for all the storage alternatives have been presented in Figure 3. The input data for the MCDM model was obtained using the secondary data sources [43-44, 52-53].

In Table 1, there are eight quantitative criteria. Quantitative criteria may be entered into software without any changes. However, the values of the six quantitative criteria were not appropriate. For instance, energy density (EneD) for PHS storage is 2 Wh/L and it is 770 for hydrogen fuel cells (HFC), which can be interpreted as “HFC is 385 times better than PHS”. However, AHP method encourages the nine times better or worse preferences. Moreover, Visual PROMETHEE software accepts the quantitative data in integer form, but some values in the quantitative data were significantly less than 1.00 (in fraction form). Hence, these criteria were converted to the qualitative scale (Table 2). Only two criteria, including round-trip efficiency (RouT) and lifetime (LT), were entered into the software as original quantitative values.

Table 1. Input data for multi-criteria storage selection problem

Main/ Level-1 criteria	Level-2 criteria	Level-3 criteria	No.	Storage alternatives														
				1 PHS	2 CAS	3 FS	4 SCS	5 STS	6 SMES	7 HFC	8 LIB	9 LAB	10 VRB	11 SSB	12 NCB	13 ZBB	14 NMH	15 SNC
Energy flow management (EFM)		TrCon	1	L-	L-	H+	M+	L-	H+	M+	H+	M+	M+	L	L	M	L	L
	Esha	BiSh	2	L	L	H+	H+	L	M	M	H+	H+	M	H+	H+	M	H	H
		TelB	3	L	L	M+	M+	L	L+	M+	M+	H+	M	M+	M+	M	M+	M+
	IntmR	VRed	4	L	L	H+	H+	L	M+	M+	H+	H+	M+	H+	H+	M+	H+	H+
		FSup	5	L	L	H+	H+	L	H+	L	H+	H+	M+	M+	M+	M+	M+	H+
		TShi	6	H+	H+	L	L	M+	L	M+	H+	H+	M+	M+	H+	M+	L	L
		PSha	7	H+	H+	M+	M+	M+	M+	M+	H+	H+	M+	H+	H+	M+	H+	H+
	DemM	LLev	8	H+	H+	M+	M+	M+	M+	M+	H+	H+	M+	H+	H+	M+	L	M+
		SpiR	9	L-	M+	M+	L-	L+	M+	M+	H+	H+	M+	M+	H+	M+	H+	M+
		StR	10	M+	M+	L	L	L+	L	M+	M+	M+	M+	M+	M+	M+	L+	L+
		PWBA	11	M+	H-	L	L	L	L	M+	H+	H+	M+	H+	H+	H+	H+	H+
		EmPS	12	L-	H-	H+	L	L	L	M+	H+	H+	H+	H+	H+	H+	H+	H+
	FaiM	DisM	13	L-	L-	M+	H+	L-	M+	L-	H+	M+	M+	H+	M+	M+	M+	H+
		BlacA	14	L	H+	L-	L-	M	L-	M+	M+	H+	H+	H+	H+	H+	H+	M+
Technical aspects (Tech)	-	EneD (Wh/L)	15	2	20	80	35	250	13.8	770	693	100	90	345	300	70	300	160
	-	ChaT	16	H+	H+	H+	H+	H	H+	H+	M+	L-	H	L-	M	M	L+	L
	-	DisD (hours)	17	8	5	0.25	0.17	18	0.008	24	5	5	10	7	8	8	4	8
	-	SDis	18	H+	H	L-	L+	H+	M	H+	H	H	H+	M-	M-	H	M-	L+
	-	RouT (%)	19	85	89	95	98	72	95	47	97	90	85	92	90	75	85	90
	-	PDen (kW/m3)	20	1.5	2	2000	4500	30	4000	35	800	400	33	50	141	25	588	300
	-	PRat (MW)	21	1000	400	20	0.1	300	10	50	100	40	100	34	50	10	3	3
Sustainability (Sust)	EcoS	PCos (US$/kW)	22	4300	1000	700	480	400	489	10200	4000	900	9444	3300	1500	2500	530	10000
		ECos (US $/kWh)	23	100	120	14000	2000	60	10854	13000	4000	1100	2000	900	3500	1000	5529	345
		ToxM	24	H+	H+	H+	H	H+	H+	H	M+	L+	M+	H-	L+	M	M+	M+
	EnvS	Recy	25	H+	H+	H	H	H+	H	M	H	H+	H+	H	H	H+	H	M
		LT (years)	26	60	40	20	10	30	30	20	16	15	20	20	20	20	15	11
		EnvI	27	H+	H+	H+	H	H+	H	H	M	L+	H-	H-	L+	M	L+	H-
		PeoS	28	L	M	H+	H+	M+	H+	L+	L+	M+	H+	L+	L+	L	L+	L+
	SocS	AccP	29	L	L	H+	H+	L	H+	H+	H-	M+	H	H+	M-	M	M	H
		EaUs	30	L	L	H+	H+	H+	H+	H+	H+	H+	H+	H+	H+	H+	H+	H+

Table 2. Conversion of inappropriate quantitative data into qualitative scale

Level-2 criteria	No.	1 PHS	2 CAS	3 FS	4 SCS	5 STS	6 SMES	7 HFC	8 LIB	9 LAB	10 VRB	11 SSB	12 NCB	13 ZBB	14 NMH	15 SNC
EneD (Wh/L)	15	L-	L-	L	L-	L+	L-	H+	H	L	L	M-	M-	L-	M-	L
DisD (hours)	17	L+	L	L-	L-	H-	L-	H+	L	L	M-	L+	L+	L+	L	L+
PDen (kW/m3)	20	L-	L-	M-	H+	L-	H	L-	L	L	L-	L-	L-	L-	L	L
PRat (MW)	21	H+	M-	L-	L-	L+	L-	L-	L-	L-	L-	L-	L-	L-	L-	L-
PCos (US$/kW)	22	M+	H+	H+	H+	H+	H+	L-	M+	H+	L-	H-	H	H	H+	L-
ECos (US $/kWh)	23	H+	H+	L-	H	H+	L	L-	L+	H+	H	H+	H-	H+	M+	H+

D. PROBLEM SOLUTION USING AHP

The AHP method involves complex mathematics, which triggered the development of the sophisticated software for the efficient solution. This paper uses SuperDecisions software for the implementation of AHP method. The implementation of AHP method involves the following steps [54-55].

Let

d	Deviation between two alternatives
n	Number of elements (i.e. criteria and alternatives) to be compared
$\lambda_{\max}$	Maximum eigenvalue
v	The eigenvector
X_i	Non-zero vector
r	Random pairwise comparisons
CR	Consistency ratio
CI	Consistency index
RI	Randomness index
A	Comparison matrix
i	Line in the matrix
j	Column in the matrix

The first stage in the implementation of AHP method is the construction of the problem hierarchy. The hierarchy of the storage selection model has been presented and explained above (Figure 2). After the hierarchy development, the pairwise comparison is performed. The AHP method works on the principle of the pairwise comparison between criteria as well as between alternatives. Each alternative and each criterion are pairwise compared with respect to the immediate upper-level criteria or goal. The AHP method uses a 9-point rating scale for comparison [56]. This paper uses a 9-point scale based on Reference [44]. This scale includes nine levels including H+, H, H-, M+, M, M-, L+, L, and L-. In this scale, H+ means “Highly Promising" and `” L-" means the “Least Promising’. For further details, the exiting literature may be referred [43-44].

In the pairwise comparisons, the $n \times n$ dimensional square matrix is obtained, which indicates the significance of each criterion or alternative. This matrix contains the criterion/alternative comparison values in the colums and rows. Equation (1) presents the property of $n \times n$ matrix A.

$$\left[a_{ij} \right], \text{ where, } i, j = 1, 2, 3, ..., n \tag{1}$$

Equation (2) shows that the two identical criteria or alternatives cannot be compared, and all the values on the diagonal of the matrix are equal to 1.

$$a_{ij} = 1 \text{ for } i = j \tag{2}$$

Equation (3) shows that the preferences will be reciprocal.

$$a_{ij} = \frac{1}{a_{ji}} \text{ for } i \neq j \tag{3}$$

Equation (4) shows that the total number of comparisons in a pairwise comparison will be as follows.

$$\frac{n(n-1)}{2} \tag{4}$$

Matrix A can also be represented as follows.

$$A = \begin{vmatrix} a_{11} & a_{12} & . & . & a_{1n} \\ a_{21} & a_{22} & . & . & a_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ a_{n1} & a_{n2} & . & . & a_{nn} \end{vmatrix} \tag{5}$$

The characteristic function of the above matrix is used to calculate the eigenvector. The eigenvector should match the maximum eigenvalue of the matrix A. The characteristic function of the matrix A is given as follows.

$$f(\lambda) = |A - \lambda \mathrm{I}| = \begin{vmatrix} a_{11} - \lambda & a_{12} & . & . & a_{1n} \\ a_{21} & a_{22} - \lambda & . & . & a_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ a_{n1} & a_{n2} & . & . & a_{nn} - \lambda \end{vmatrix} \tag{6}$$

Eigenvectors of the matrix A are each column and the non-zero vector X_i.

$$(A - \lambda_i) X_i = 0 \tag{7}$$

If $X_i = v$ for $\lambda_{\max}$, the eigenvector is the solution to the following equation.

$$Av = \lambda_{\max} v \tag{8}$$

In the following, the eigenvector corresponding to $\lambda_{\max}$ has been derived using the normalised arithmetic averages. First, the normalization of matrix A is performed so that the very large or very small values can be avoided [57]. Consequently, matrix A is transformed to matrix B.

$$B = \left[b_{ij} \right] \quad (9)$$

The elements of normalized pairwise comparison matrix are obtained using the following equation.

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (10)$$

Then, the preferences between the different criteria or alternatives are calculated using the eigenvector $v = \left[v_i \right]$. For this purpose, the arithmetic average is calculated as follows.

$$v_i = \frac{\sum_{j=1}^{n} b_{ij}}{n} \quad (11)$$

Maximum eigenvalue $\lambda_{\max}$ is calculated as follows.

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{\left(Av \right)_i}{v_i} \quad (12)$$

After the pairwise comparisons, the consistency of the AHP model is determined. The AHP method works well if the pairwise comparison is the highly consistent. Consequently, the consistency test is performed. For this purpose, the consistency index (CI) is calculated as follows.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (13)$$

The consistency ratio of the comparison matrix is given below.

$$CR = \frac{CI}{RI} = \frac{CI}{Random\ average\ CI} = \frac{\lambda_{\max} - n}{r\left(n - 1 \right)} 100\% \quad (14)$$

The consisitency ratio should be maximum 10%. If it is greater than 10%, the decision maker should review the pairwise comparison data until the inconsistency is acceptable [58].

E. PROBLEM SOLUTION USING PROMETHEE

PROMETHEE is based on the pairwise comparison of the alternatives. In this paper, the alternatives were evaluated based on the PROMETHEE-I (partial ranking) and PROMETHEE-II (complete ranking). This paper uses Visual PROMETHEE software (academic edition) for the implementation of PROMETHEE method. The implementation of PROMETHEE method involves the following steps [59-61].

Let

y Index of the evaluation criteria, where $y = 1, 2, 3, \ldots Y$

Z Set of finite alternatives, where $Z = \left\{ a_1, a_2, a_3, \ldots, N \right\}$, $a, b, x \in Z$

w_y Weights associated with criterion y

$g_y(a)$ Value of criterion y for alternative a

$g_y(b)$ Value of criterion y for alternative b

The first stage in the implementation of PROMETHEE method is to define the criteria and alternatives. In this paper, the criteria and alternatives for PROMETHEE method were same as in AHP method. Then, the weight w_y is assigned to each criterion y. In this paper, relative weights of the criteria were taken from AHP model. Hence, the relative importance of all the criteria was set same in AHP and PROMETHEE methods. In PROMETHEE, the weights for all the criteria should satisfy the following condition.

$$\sum_{y=1}^{Y} w_y = 1 \quad (15)$$

After the problem definition, the next step is to compute the deviations between the different alternatives through pairwise comparisons. The deviations between the values of the two alternatives a and b for each criterion can be calculated as follows.

$$d_y \left(a, b \right) = g_y(a) - g_y(b) \qquad a, b \in Z \quad (16)$$

The next step is to define the preference function. This method requires the preference functions, which are used to define the deviations between different alternatives for each criterion. The preference function can be defined as follows.

$$P_y \left(a, b \right) = F_y \left[d_y \left(a, b \right) \right]$$

Where, $0 \le P_y \left(a, b \right) \le 1$ (17)

The preference function $P_y \left(a, b \right)$ is the function of the difference between evaluations of alternative a regarding the alternative b for each criterion. The different types of preference functions can be used in PROMETHEE method. This paper used the two preference functions including "Usual" and "Linear" types. The preference function "Usual" was used for the qualitative scale and preference function “Linear” was used for the quantitative values. The preference function “Usual” can be defined as follows.

$$P(d)=\begin{cases}0, & for\ d \le 0\\ 1, & for\ d > 0\end{cases} \tag{18}$$

And the preference function “Linear” can be defined as follows.

$$P(d)=\begin{cases}0, & d<0\\ \dfrac{d}{m}, & 0 \le d \ge 0\\ 1, & d>m\end{cases} \tag{19}$$

In this function, linearity of preference function increases until point *m*. This point is arbitrary, and the decision maker should fix it. In the next step, the aggregated preference indices are calculated in the PROMETHEE method. For this purpose, the overall preference index can be calculated as follows.

$$\begin{cases}\pi(a,b)=\sum_{y=1}^{Y} P(a,b)w_y, \\ \pi(b,a)=\sum_{y=1}^{Y} P(b,a)w_y, \end{cases} \quad a,b \in Z \tag{20}$$

The preference index $\pi(a,b)$ is the degree to which a is preferred to b over all the criteria. Similarly, $\pi(b,a)$ is the degree to which b is preferred to a over all the criteria. In the next step, the ranking is made using the PROMETHEE-I and PROMETHEE-II. The PROMETHEE I or the partial ranking can be obtained through the positive and negative outranking flows. An alternative with the highest value of the positive outranking flow is the best alternative. The positive outranking flow can be computed as follows.

$$\phi^{+}(a)=\frac{1}{N-1}\sum_{x\in Z}\pi(a,x) \qquad x \in Z \tag{21}$$

Each alternative a is compared with $N-1$ other alternatives in *Z*. Similary, an alternative with the lowest value of the negative outranking flow is the best alternative. The negative outranking flow can be computed as follows.

$$\phi^{-}(a)=\frac{1}{N-1}\sum_{x\in Z}\pi(x,a) \qquad x \in Z \tag{22}$$

Usually, all the alternatives may not be comparable. In this situation, the complete ranking or PROMETHEE-II is performed through the computation of the net outranking flow. The net outranking flow can be computed as follows.

$$\phi(a)=\phi^{+}(a)-\phi^{-}(a) \tag{23}$$

F. HYBRID STORAGE SELECTION BASED ON AHP AND PROMETHEE SOLUTIONS

Once the storage rankings were received from both methods, an iterative novel procedure was implemented for the selection of the best storage technology. Firstly, the common alternatives were discarded from the specified number of the least ranked alternatives in both methods. For this purpose, this paper selected the five least ranked alternatives from the individual solution of AHP and PROMETHEE. From these five least ranked alternatives, the common alternatives were excluded. Then, the AHP and PROMETHEE models were solved again using the remaining alternatives. From the new solutions by each method, the five least ranked alternatives were selected, and the common alternatives were excluded again. This procedure was repeated until the best alternative was achieved. For the purpose of discarding the common alternatives, this paper selected five least ranked alternatives from the solution. However, when the number of alternatives in the problem became less than or equal to five, then the number of discarded alternatives were less than five. The decision makers may change the number of discarded alternatives according to the suitability of the problem.

III. RESULTS AND DISCUSSION

In the following, the proposed methodology has been applied on the two different cases, and the key results have been presented.

A. CASE 1. ALL THE THREE MAIN CRITERIA ARE EQUALLY PREFERABLE

In this case, it was assumed that the energy flow management for prosumers, technical aspects, and sustainability should be given equal importance in the decision making. This case has been evaluated in the following based on the AHP and PROMETHEE methods.

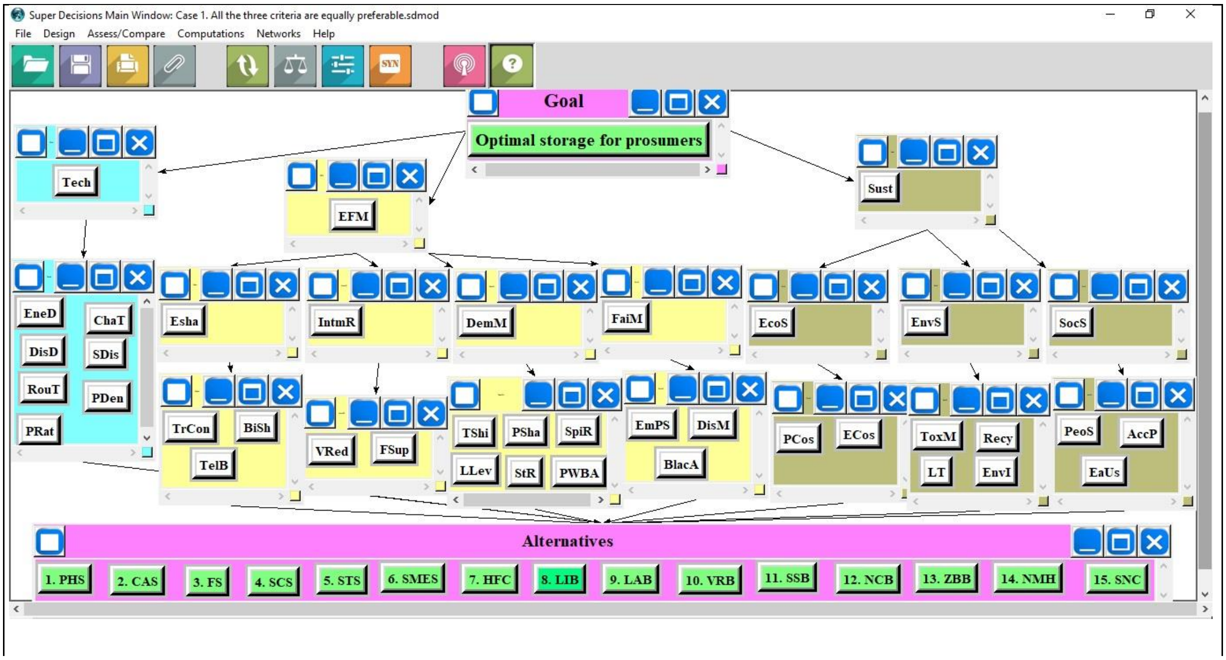


Figure 4. AHP storage selection model structure in Super Decisions software

1) AHP MODEL EVALUATION FOR THE CASE 1

In AHP model, the preferences for the different criteria and alternatives were set as follows. In Case 1, the level 1 criteria in the hierarchy (i.e. energy flow management for prosumers, technical aspects, and sustainability) were kept equally (i.e. one time) preferably with respect to goal. Similarly, the level 2 criteria and level 3 criteria were kept equally preferable with respect to immediate upper-level criteria. Finally, the preferences of the storage alternatives were set based on the actual data in Table 1 and Table 2. Figure 4 presents the AHP model structure in the SuperDecisions software.

Name	Graphic	Ideals	Normals	Raw
1. PHS		0.885410	0.066581	0.018158
2. CAS		0.836767	0.062923	0.017161
3. FS		0.852916	0.064137	0.017492
4. SCS		0.998363	0.075075	0.020475
5. STS		0.851557	0.064035	0.017464
6. SMES		0.939323	0.070635	0.019264
7. HFC		0.891489	0.067038	0.018283
8. LIB		1.000000	0.075198	0.020508
9. LAB		0.942203	0.070852	0.019323
10. VRB		0.899986	0.067677	0.018457
11. SSB		0.897767	0.067510	0.018412
12. NCB		0.860271	0.064690	0.017643
13. ZBB		0.826539	0.062154	0.016951
14. NMH		0.820030	0.061664	0.016818
15. SNC		0.795642	0.059831	0.016317

Figure 5. Case 1. AHP model solution

Figure 5 presents the AHP model solution based on Case 1. AHP results contain three columns. The column "Raw" contains the model solution extracted from the Limit Supermatrix. The columns "Ideals" and "Normals" were derived from the column "Raw" for the purpose of easy understanding. The column "Normals" was derived by dividing an individual value with sum of all the values within "Raw" column. The column "Ideals" was derived by dividing an individual value with the largest value within "Raw" column. According to Figure 5, the lithium-ion battery (LIB) was found as a best storage alternative for the prosumers in smart grids. However, the supercapacitors (SCS) and lead acid battery (LAB) were found as the 2nd and 3rd options. Hence, the supercapacitors may be used with lithium-ion batteries. The supercapacitors would not offer some of the major requirements in the prosumer-based smart grids. In this situation, the lead acid battery would be the next option. Several other storage technologies have received a good ranking, but lithium-ion battery has been selected as a best alternative in the Case 1.

In the AHP model solutions, the inconsistency was ensured negligible. For instance, Figure 6 presents the data entry window for the criteria "transmission stability and congestion management (TrCon)". For this criterion, the pairwise comparison of all the 15 storage technologies was performed as shown in the left side of the window. In the right side, the inconsistency value is displaying at the top of results. The inconsistency of the pairwise comparisons for this criterion is zero. Similarly, all the other criteria exhibited zero or negligible inconsistency, which shows the high reliability of the pairwise comparisons.

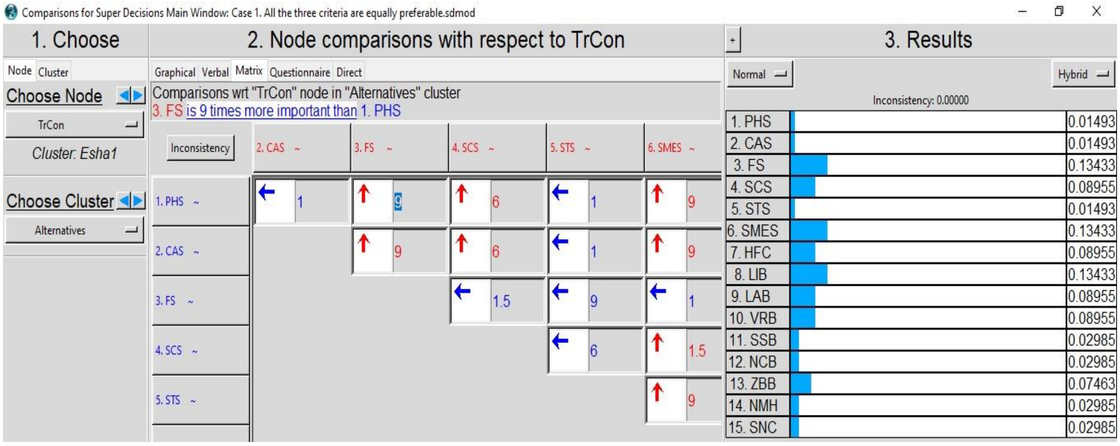


Figure 6. Data entry and inconsistency test for the pairwise comparison

2) PROMETHEE MODEL EVALUATION FOR THE CASE 1

In PROMETHEE model, the preferences weights for the level 1 criteria, level 2 criteria, and level-3 criteria were obtained from AHP model. The preferences of the storage alternatives were set based on the actual data in Table 1 and Table 2. Figure 7 presents the upper left part of the PROMETHEE model structure in the Visual PROMETHEE software.

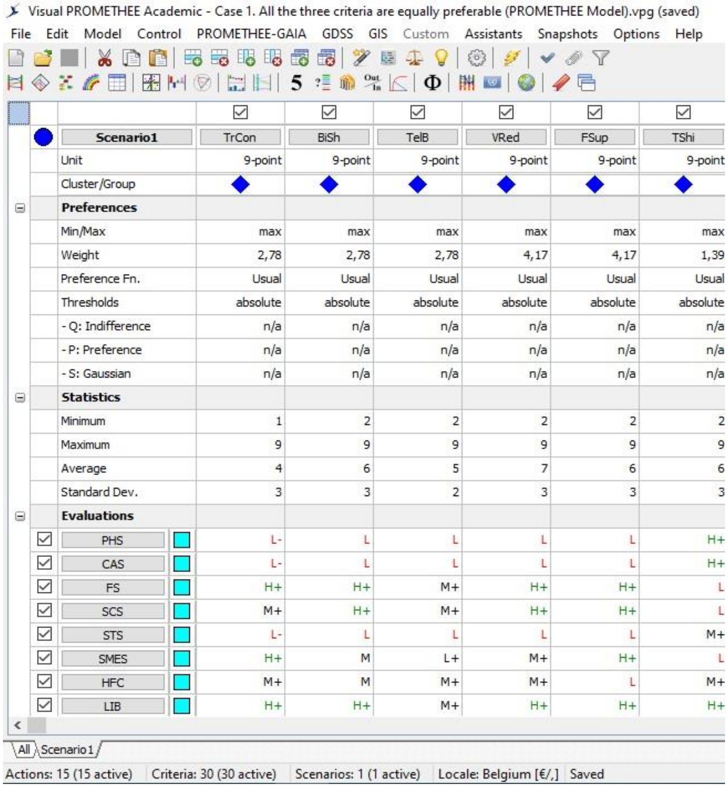
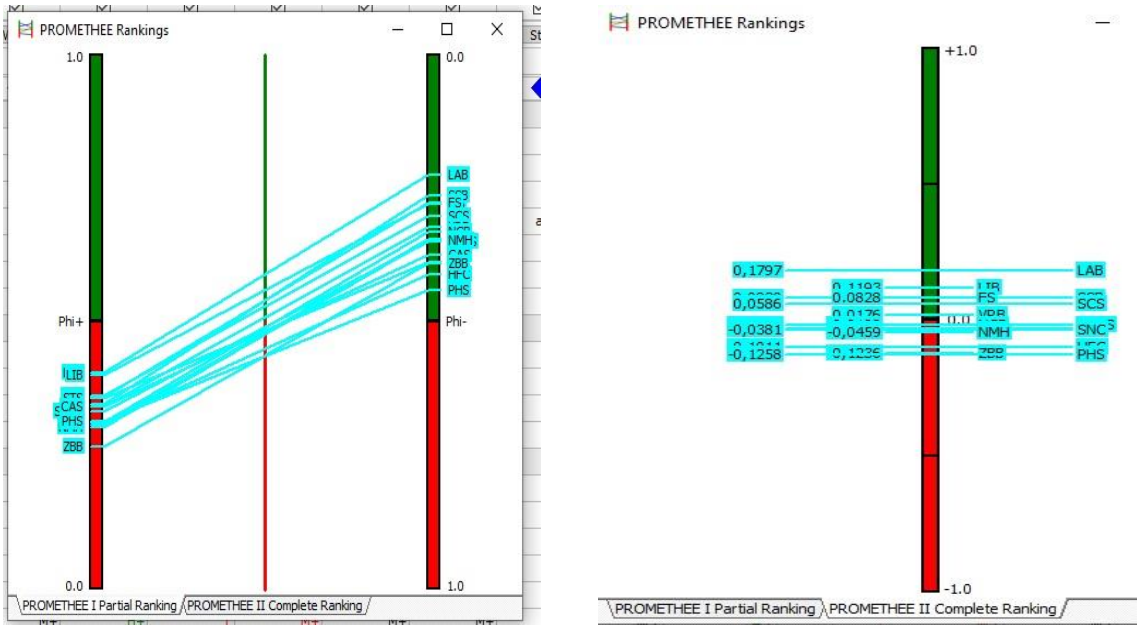


Figure 7. Case 1. PROMETHEE model structure in Visual PROMETHEE software



(a) PROMETHEE I Partial Ranking **(b)** PROMETHEE II Complete Ranking

Figure 8. Case 1. PROMETHEE model solution

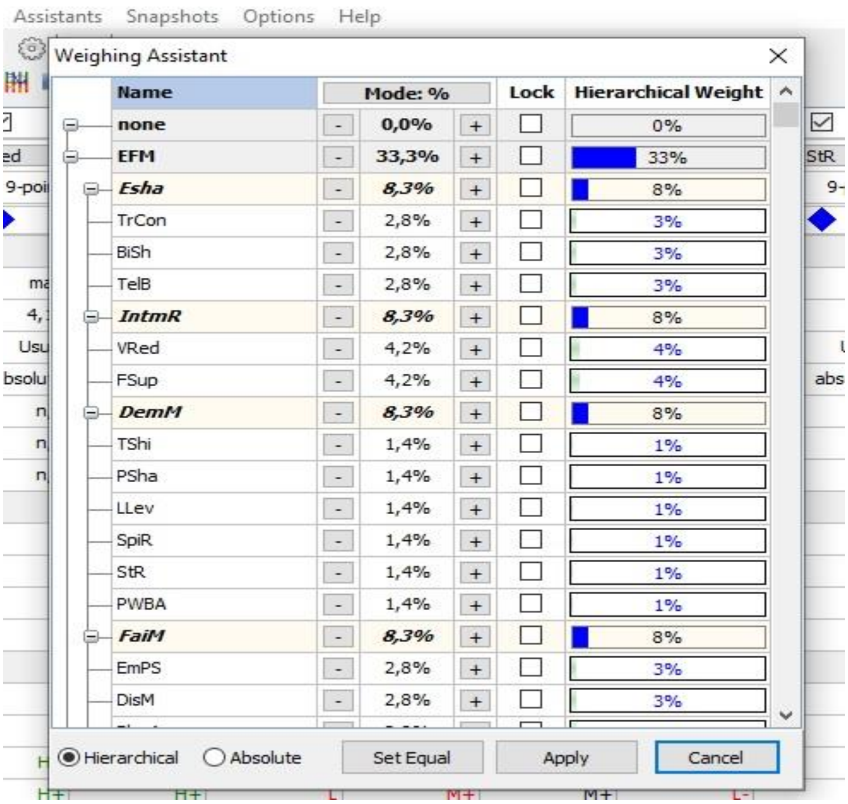
Figure 8 presents the PROMETHEE model solution based on Case 1. This method suggested the lead acid battery (LAB) as first choice for both PROMETHEE I and PROMETHEE II. The storage alternatives are overlapped in Figure 8 due to very close scores. Figure 9 presents these values in a clearer form. According to PROMETHEE I, the lithium-ion battery (LIB) has the 2nd ranking based on the better Phi+ scores, but it has worse scores on Phi-. Hence, the priority of LIB is not clear, but it can be confirmed with PROMETHEE II. According to PROMETHEE II complete ranking, LIB has the second priority and LAB has a priority. In contrast, AHP model offered the first priority for LIB and the third priority for LAB. Hence, the AHP and PROMETHEE methods offered somewhat different solutions.

Visual PROMETHEE software contains the criteria names along the horizontal direction in rows, and the alternatives names (i.e. evaluations) along the vertical direction in columns. In the evaluations window, the qualitative and numerical data can be entered directly. The software allows the hierarchy development using the “Criteria Hierarchy Assistant” window. Also, the weights can be assigned using the “Weighing Assist” window. For instance, Figure 10 presents the upper part of the “Weighing Assistant” windows.

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	LAB	0,1797	0,4052	0,2255
2	LIB	0,1193	0,3990	0,2797
3	SSB	0,0830	0,3465	0,2635
4	FS	0,0828	0,3595	0,2767
5	SCS	0,0586	0,3612	0,3026
6	VRB	0,0176	0,3407	0,3231
7	SMES	-0,0194	0,3314	0,3508
8	NCB	-0,0198	0,3117	0,3316
9	STS	-0,0326	0,3557	0,3883
10	CAS	-0,0347	0,3409	0,3756
11	SNC	-0,0381	0,3077	0,3458
12	NMH	-0,0459	0,3029	0,3488
13	HFC	-0,1011	0,3114	0,4125
14	ZBB	-0,1236	0,2670	0,3907
15	PHS	-0,1258	0,3146	0,4404

Figure 9. Case 1. PROMETHEE model solution



Assistants Snapshots Options Help

Weighing Assistant

Name	Mode: %	Lock	Hierarchical Weight
none	0,0%		0%
EFM	33,3%		33%
Esha	*8,3%*		8%
TrCon	2,8%		3%
BiSh	2,8%		3%
TelB	2,8%		3%
IntmR	*8,3%*		8%
VRed	4,2%		4%
FSup	4,2%		4%
DemM	*8,3%*		8%
TShi	1,4%		1%
PSha	1,4%		1%
LLev	1,4%		1%
SpiR	1,4%		1%
StR	1,4%		1%
PWBA	1,4%		1%
FaiM	*8,3%*		8%
EmPS	2,8%		3%
DisM	2,8%		3%

Hierarchical Absolute Set Equal Apply Cancel

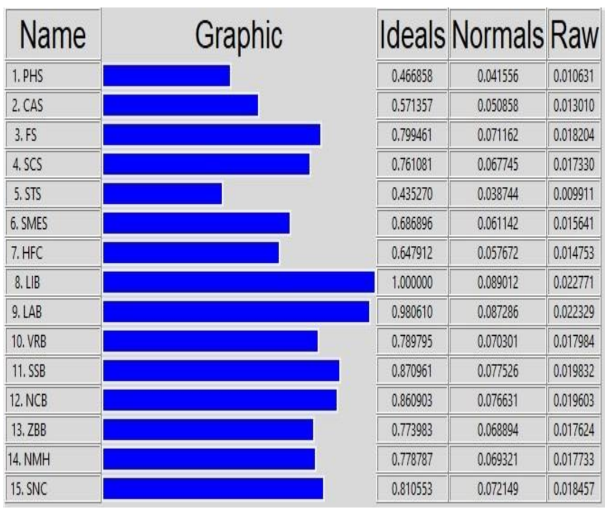
Figure 10. Weighing Assistant window in Visual PROMETHEE software (Case 1)

C. CASE 2. ENERGY FLOW MANAGEMENT FOR PROSUMERS IS EXTREMELY MORE PREFERABLE

In this case, it was assumed that the main criteria "energy flow management for prosumers" is extremely more preferable than the remaining two main criteria. This case has been evaluated in the following based on the AHP and PROMETHEE methods.

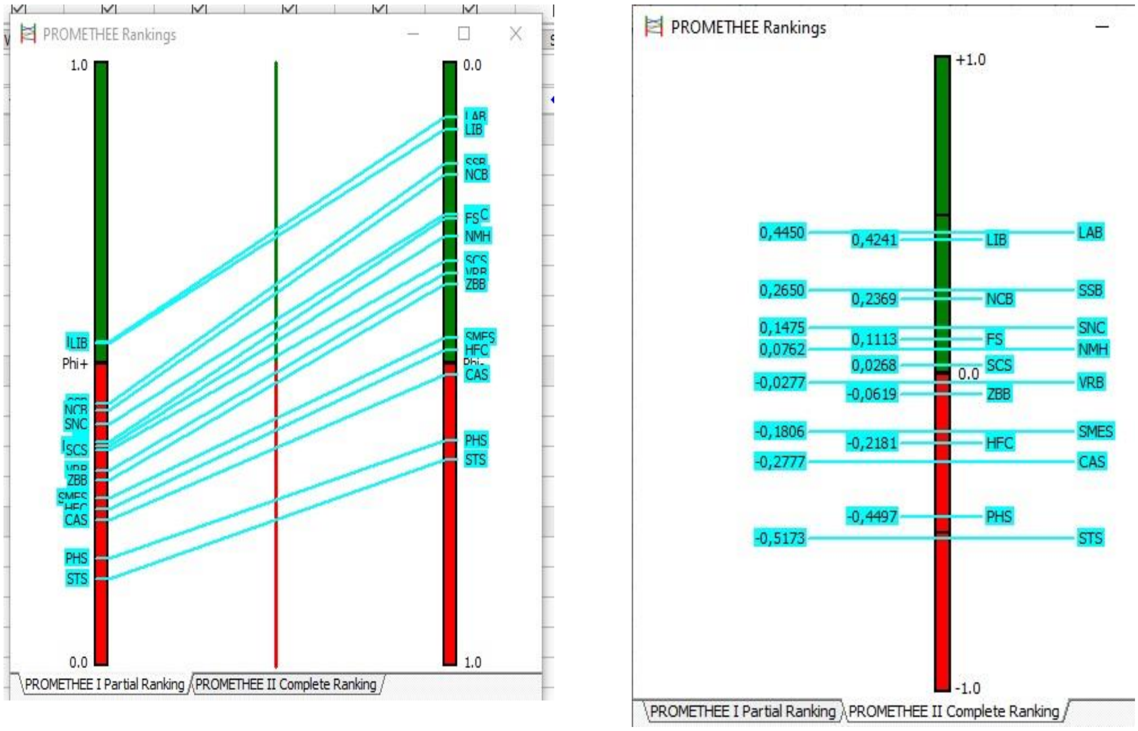
1) AHP MODEL EVALUATION FOR THE CASE 2

In AHP model, the preferences for different criteria and alternatives were set as follows. In Case 2, the level 1 criteria "energy flow management for prosumers" was set extremely (i.e. nine times) more preferable than the remaining two main criteria "technical aspects" and "sustainability" with respect to goal. The preferences for the level 2 criteria, level 3 criteria, and alternatives were set same as in Case 1. However, the preferences for the level 2 criteria and level 3 criteria were affected, resulting in the entirely different values of the preferences weights compared with Case 1. Figure 11 presents the AHP model solution based on Case 2. The lithium-ion battery (LIB) was found as the first storage alternative for the prosumers in smart grids. However, the lead acid battery (LAB) and sodium sulfur battery (SSB) were found as the 2nd and 3rd options, respectively. In the absence of the lithium ion (LIB), LAB and SSB would be the next option. Several other storage technologies have received a good ranking, but LIB has been selected as the best alternative in Case 2.



Name	Graphic	Ideals	Normals	Raw
1. PHS		0.466858	0.041556	0.010631
2. CAS		0.571357	0.050858	0.013010
3. FS		0.799461	0.071162	0.018204
4. SCS		0.761081	0.067745	0.017330
5. STS		0.435270	0.038744	0.009911
6. SMES		0.686896	0.061142	0.015641
7. HFC		0.647912	0.057672	0.014753
8. LIB		1.000000	0.089012	0.022771
9. LAB		0.980610	0.087286	0.022329
10. VRB		0.789795	0.070301	0.017984
11. SSB		0.870961	0.077526	0.019832
12. NCB		0.860903	0.076631	0.019603
13. ZBB		0.773983	0.068894	0.017624
14. NMH		0.778787	0.069321	0.017733
15. SNC		0.810553	0.072149	0.018457

Figure 11. Case 2. AHP model solution



(a) PROMETHEE I Partial Ranking (Case 2) (b) PROMETHEE II Complete Ranking (Case 2)

Figure 12. Case 2. PROMETHEE model solution

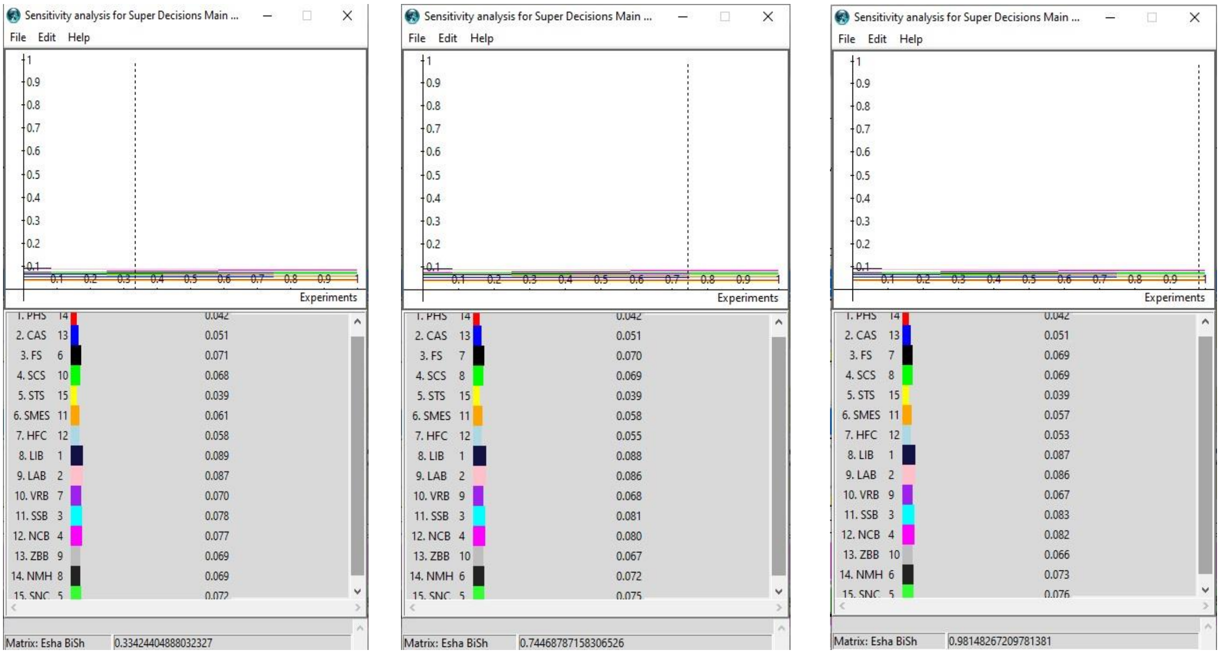
2) PROMETHEE MODEL EVALUATION FOR THE CASE 2

In PROMETHEE model, the preferences for the criteria and alternatives were same as in Case 2 for the AHP model. Figure 12 presents the PROMETHEE model solution based on the Case 2. This method suggested the lead acid battery (LAB) as the first choice for both PROMETHEE I and PROMETHEE II. However, the lithium-ion battery (LIB) and sodium sulfur battery (SSB) were found as the 2nd and 3rd options, respectively. In the absence of the LAB, the LIB and SSB would be the next option. It can be observed that the AHP and PROMETHEE resulted in more comparable ranking than the Case 1. It can also be observed that the storage alternatives are less overlapping compared with Case 1, which resulted in more clear rankings of the storage alternatives for both PROMETHEE I and PROMETHEE II.

C. SENSITIVITY ANALYSIS

In the following, the sensitivity analysis has been performed for the AHP and PROMETHEE solutions. In AHP and PROMETHEE models, the sensitivity analysis was performed by changing the weights of the criteria. Both software (i.e. SuperDecisions and Visual PROMETHEE) offer sensitivity analysis based on the changes in the weights or priorities for a criterion. The results confirmed that the variations in the priorities for the different criteria did not significantly affect the model solutions.

We consider a sub-criterion "support in bidirectional energy sharing (BiSh)" in Case 2 for the sensitivity analysis. The criterion "Energy Sharing (Esh)" contains the three sub-criteria including support in bidirectional energy sharing (BiSh), transmission stability and congestion management (TrCon), and telecommunications backup (TelB). In Case 2, these criteria are equally preferable. In AHP method, these three sub-criteria correspond to the approximate priority 0.33 out of 1.00. However, PROMETHEE software allowed the direct entry of criteria weight in percentage (i.e. 0-100%). In PROMETHEE method, a maximum 20.45% weight was allowed to the criteria "Energy Sharing (Esh)". Consequently, 20.45% in PROMETHEE method is exactly equal to 1.00 in AHP method.

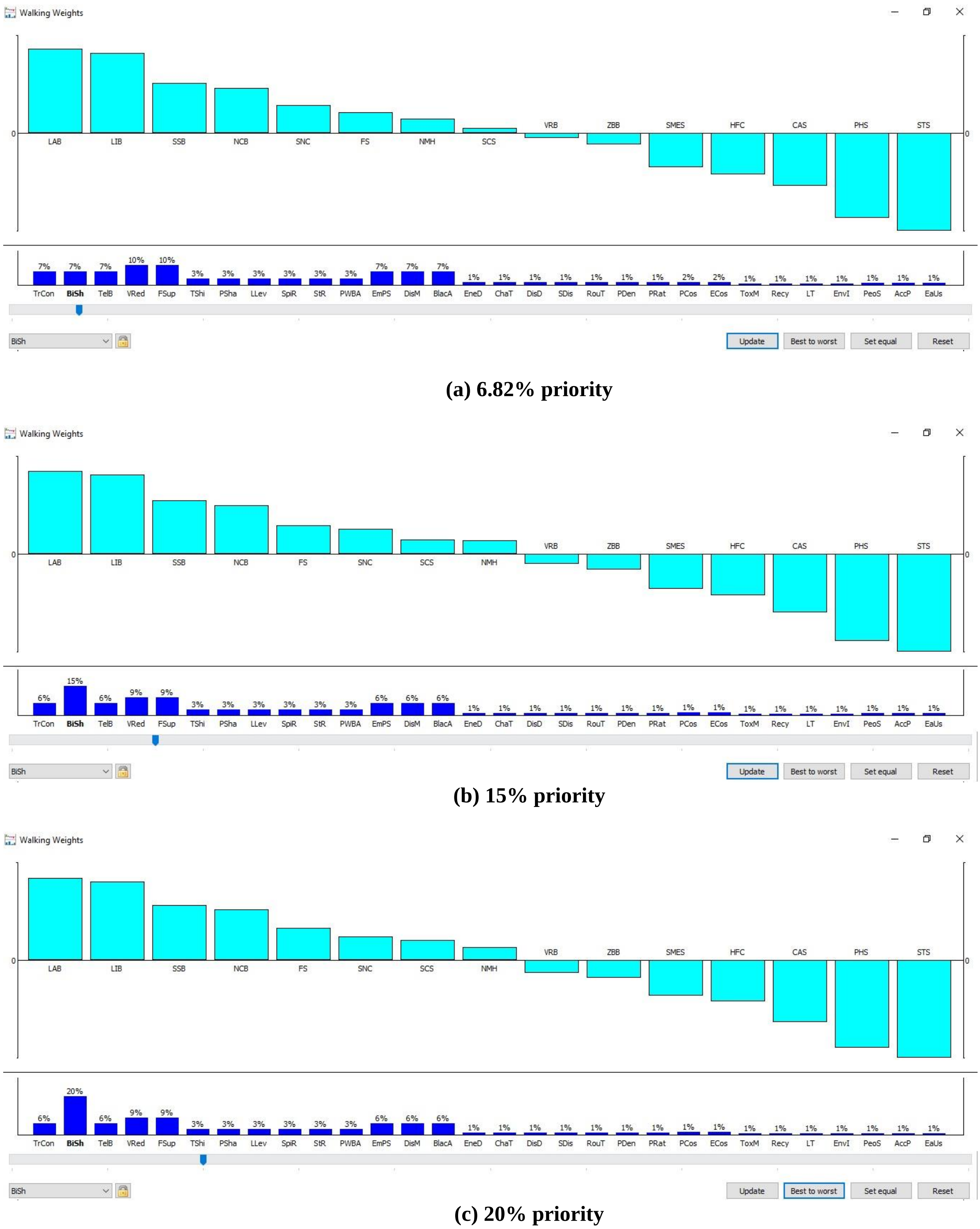


6.82% priority **15% priority** **20% priority**

Figure 13. Sensitivity analysis of AHP solution for Case 2

Table 3. Comparison of sensitivity analysis results

Ranking	AHP model			PROMETHEE model		
	6.82% priority	15% priority	20% priority	6.82% priority	15% priority	20% priority
1	LIB	LIB	LIB	LAB	LAB	LAB
2	LAB	LAB	LAB	LIB	LIB	LIB
3	SSB	SSB	SSB	SSB	SSB	SSB
4	NCB	NCB	NCB	NCB	NCB	NCB
5	SNC	SNC	SNC	SNC	FS	FS
6	FS	NMH	NMH	FS	SNC	SNC
7	VRB	FS	FS	NMH	SCS	SCS
8	NMH	SCS	SCS	SCS	NMH	NMH
9	ZBB	VRB	VRB	VRB	VRB	VRB
10	SCS	ZBB	ZBB	ZBB	ZBB	ZBB
11	SMES	SMES	SMES	SMES	SMES	SMES
12	HFC	HFC	HFC	HFC	HFC	HFC
13	CAS	CAS	CAS	CAS	CAS	CAS
14	PHS	PHS	PHS	PHS	PHS	PHS
15	STS	STS	STS	STS	STS	STS



(a) 6.82% priority

(b) 15% priority

(c) 20% priority

Figure 14. Sensitivity analysis of PROMETHEE solution for Case 2

In the Case 2, the criterion “support in bidirectional energy sharing (BiSh)” has 6.82% weight out of 20.45%. Consequently, 6.82% in PROMETHEE method is exactly equal to 0.33 in AHP method. In the sensitivity analysis, the weight of this criterion was steadily increased from 6.82% to 20% for PROMETHEE method and 0.33 to 1.00 for AHP method. In this section, only three priority levels (i.e. 6.82%, 15%, and 20%) have been presented. In AHP method, 6.82%, 15%, and 20% were equivalent to 0.33, 0.74, and 0.98, respectively. In summary, the sensitivity analysis was performed with similar priorities for AHP and PROMETHEE methods.

Figure 13 presents the sensitivity analysis of AHP solution for the three different priority levels. The horizontal axis shows the priority of a criterion, and the vertical axis shows the storage rankings. It can be observed that most of the storage alternatives have occupied similar rank for each priority level of the criterion “support in bidirectional energy sharing (BiSh)”. The remaining alternatives exhibited only slightly different ranks (i.e. 1 or 2 ranks more or less) for the three priority levels. Similar trends can be observed for the sensitivity analysis of PROMETHEE solution (Figure 14). Table 3 presents the comparison of the sensitivity analysis results based on the criterion “support in bidirectional energy sharing (BiSh)”. It can be observed that most of the rankings are same or slightly different for the priority levels of the criterion “support in bidirectional energy sharing (BiSh)”. Similar trends were observed for the remaining criteria in both methods. It was found that the results were very stable for the AHP and PROMETHEE solutions.

D. HYBRID DECISION MAKING BASED ON AHP AND PROMETHEE

In the above sections, AHP and PROMETHEE methods offered somewhat different solutions. This difference in the problem solutions is due to the fact that both methods have different mathematical backgrounds and calculations, resulting in different solutions. There should be some ways to combine the AHP and PROMETHEE solutions, so that the best most reliable storage technology can be identified. In the following, a collective decision-making approach has been proposed based on the solutions of both AHP and PROMETHEE methods. Figure 15 presents the systematic detection of the best storage alternatives from AHP and PROMETHEE solutions for Case 1. In Case 1, all the three main criteria were given equal priority as discussed in Section 3.1.

Please refer to Section 2.6 for the hybrid storage selection procedure adopted in this section. In the first step, all the 15 storage technologies were included. In this step, the problem and solution were exactly same as the individual models of AHP and PROMETHEE. In this step, the AHP (left side) and PROMETHEE (right side) solutions are given in Figure 15(a). Within the last five storage alternatives in both methods, three storage technologies (i.e. ZBB, NMH, and SNC) were found common in both solutions. These three storage technologies were excluded, and the models were solved again with the remaining 12 storage options (Figure 15(b)). Amongst these 12 storage technologies, three storage technologies (i.e. NCB, PHS, and STS) were found to be common within the last five storage alternatives. These three storage technologies were excluded, and the models were solved again with the remaining nine storage options (Figure 15(c)).

This procedure was repeated again, and the HFC, CAS, SMES, VRB were excluded in the next step, and the models were solved for the remaining five alternatives (Figure 15(d)). Here, the storage alternatives were exactly five. Here, the common alternatives were excluded from the last four alternatives (Figure 15(e)). In this way, SSB, SCS, and FS were excluded from the analysis, and the models were solved for the remaining two storage alternatives. As a result, the lithium-ion battery (LIB) was ranked first, and the lead acid battery (LAB) was ranked second by both AHP and PROMETHEE methods. These results were obtained based on Case 1. This procedure was applied on the Case 2 as shown in Figure 16. In the Case 2, the main criteria “energy flow management for prosumers” was given extremely more priority (please refer Section 3.2). Again, the LIB was ranked first, and the LAB was ranked second by both methods. It can be observed that the Case 2 ranked the storage alternatives more clearly compared with the Case 1. It can be noted that the best solution is reached in four steps for Case 2 (i.e. Figure 16), while the best solution reached in five steps for Case 1 (i.e. Figure 15). The exclusion of the least ranked storage alternatives in a few steps interprets that the solutions offered by the MCDM methods are significantly identical. This fact proves the validity and reliability of the solutions offered by the two entirely different methods within the MCDM domain of operations research and management sciences.

Name	Graphic	Ideals	Normals	Raw
1. PHS		0.885410	0.066581	0.018158
2. CAS		0.836767	0.062923	0.017161
3. FS		0.852916	0.064137	0.017492
4. SCS		0.998363	0.075075	0.020475
5. STS		0.851557	0.064035	0.017464
6. SMES		0.939323	0.070635	0.019264
7. HFC		0.891489	0.067038	0.018283
8. LIB		1.000000	0.075198	0.020508
9. LAB		0.942203	0.070852	0.019323
10. VRB		0.899986	0.067677	0.018457
11. SSB		0.897767	0.067510	0.018412
12. NCB		0.860271	0.064690	0.017643
13. ZBB		0.826539	0.062154	0.016951
14. NMH		0.820030	0.061664	0.016818
15. SNC		0.795642	0.059831	0.016317

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	LAB	0,1797	0,4052	0,2255
2	LIB	0,1193	0,3990	0,2797
3	SSB	0,0830	0,3465	0,2635
4	FS	0,0828	0,3595	0,2767
5	SCS	0,0586	0,3612	0,3026
6	VRB	0,0176	0,3407	0,3231
7	SMES	-0,0194	0,3314	0,3508
8	NCB	-0,0198	0,3117	0,3316
9	STS	-0,0326	0,3557	0,3883
10	CAS	-0,0347	0,3409	0,3756
11	SNC	-0,0381	0,3077	0,3458
12	NMH	-0,0459	0,3029	0,3488
13	HFC	-0,1011	0,3114	0,4125
14	ZBB	-0,1236	0,2670	0,3907
15	PHS	-0,1258	0,3146	0,4404

(a) Solve AHP (leftside) and PROMETHEE (right side) models with all the 15 storage alternatives. In the next step, exclude ZBB, NMH, and SNC and solve.

Name	Graphic	Ideals	Normals	Raw
1. PHS		0.856372	0.079439	0.021665
2. CAS		0.824053	0.076441	0.020848
3. FS		0.846804	0.078551	0.021423
4. SCS		0.988619	0.091706	0.025011
5. STS		0.835537	0.077506	0.021138
6. SMES		0.921523	0.085482	0.023313
7. HFC		0.877158	0.081367	0.022191
8. LIB		1.000000	0.092762	0.025299
9. LAB		0.952315	0.088339	0.024092
10. VRB		0.899105	0.083403	0.022746
11. SSB		0.910135	0.084426	0.023025
12. NCB		0.868641	0.080577	0.021976

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	LAB	0,1677	0,4102	0,2425
2	LIB	0,0865	0,3951	0,3086
3	FS	0,0652	0,3466	0,2815
4	SSB	0,0578	0,3520	0,2942
5	SCS	0,0302	0,3421	0,3119
6	VRB	-0,0071	0,3394	0,3465
7	CAS	-0,0328	0,3334	0,3662
8	SMES	-0,0334	0,3188	0,3523
9	NCB	-0,0410	0,3188	0,3598
10	STS	-0,0486	0,3413	0,3899
11	HFC	-0,1219	0,2994	0,4212
12	PHS	-0,1226	0,3078	0,4304

(b) Solve models with remaining 12 alternatives. In the next step, exclude NCB, PHS, and STS and solve.

Name	Graphic	Ideals	Normals	Raw
2. CAS		0.908499	0.108848	0.029686
3. FS		0.839784	0.100616	0.027441
4. SCS		0.974079	0.116706	0.031829
6. SMES		0.908926	0.108900	0.029700
7. HFC		0.904009	0.108311	0.029539
8. LIB		1.000000	0.119811	0.032676
9. LAB		0.964265	0.115530	0.031508
10. VRB		0.918671	0.110067	0.030018
11. SSB		0.928221	0.111211	0.030330

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	LAB	0,1472	0,3914	0,2441
2	LIB	0,0682	0,3715	0,3033
3	FS	0,0521	0,3154	0,2633
4	SSB	0,0379	0,3468	0,3089
5	SCS	0,0191	0,3102	0,2911
6	CAS	-0,0476	0,3566	0,4043
7	VRB	-0,0483	0,3142	0,3626
8	SMES	-0,0634	0,2806	0,3440
9	HFC	-0,1652	0,2724	0,4376

(c) Solve models with remaining 9 alternatives. In the next step, exclude HFC, CAS, SMES, VRB and solve
.

Name	Graphic	Ideals	Normals	Raw
3. FS		0.830647	0.178261	0.048617
4. SCS		0.956130	0.205191	0.055961
8. LIB		1.000000	0.214605	0.058529
9. LAB		0.949303	0.203725	0.055561
11. SSB		0.923635	0.198217	0.054059

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	LAB	0,0795	0,3206	0,2411
2	LIB	0,0127	0,2945	0,2817
3	SSB	-0,0246	0,2889	0,3135
4	SCS	-0,0331	0,2700	0,3031
5	FS	-0,0346	0,2546	0,2892

(d) Solve models with remaining 5 alternatives. In the next step, exclude SSB, SCS, and FS and solve.

Name	Graphic	Ideals	Normals	Raw
8. LIB		1.000000	0.514656	0.140361
9. LAB		0.943046	0.485344	0.132367

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	LIB	0,0119	0,2434	0,2315
2	LAB	-0,0119	0,2315	0,2434

(e) Solve models with remaining two alternatives.

Figure 15. Determination of the best storage based on AHP and PROMETHEE solutions for Case 1.

Name	Graphic	Ideals	Normals	Raw
1. PHS		0.466858	0.041556	0.010631
2. CAS		0.571357	0.050858	0.013010
3. FS		0.799461	0.071162	0.018204
4. SCS		0.761081	0.067745	0.017330
5. STS		0.435270	0.038744	0.009911
6. SMES		0.686896	0.061142	0.015641
7. HFC		0.647912	0.057672	0.014753
8. LIB		1.000000	0.089012	0.022771
9. LAB		0.980610	0.087286	0.022329
10. VRB		0.789795	0.070301	0.017984
11. SSB		0.870961	0.077526	0.019832
12. NCB		0.860903	0.076631	0.019603
13. ZBB		0.773983	0.068894	0.017624
14. NMH		0.778787	0.069321	0.017733
15. SNC		0.810553	0.072149	0.018457

Rank	action	Phi	Phi+	Phi-
1	LAB	0,4450	0,5369	0,0919
2	LIB	0,4241	0,5351	0,1110
3	SSB	0,2650	0,4343	0,1693
4	NCB	0,2369	0,4226	0,1857
5	SNC	0,1475	0,3999	0,2524
6	FS	0,1113	0,3708	0,2595
7	NMH	0,0762	0,3640	0,2878
8	SCS	0,0268	0,3561	0,3293
9	VRB	-0,0277	0,3223	0,3500
10	ZBB	-0,0619	0,3066	0,3684
11	SMES	-0,1806	0,2765	0,4571
12	HFC	-0,2181	0,2581	0,4761
13	CAS	-0,2777	0,2402	0,5179
14	PHS	-0,4497	0,1768	0,6265
15	STS	-0,5173	0,1426	0,6599

(a) Solve AHP and PROMETHEE models with all the 15 storage alternatives. In the next step, exclude SMES, HFC, CAS, PHS, and STS and solve.

Name	Graphic	Ideals	Normals	Raw
3. FS		0.792171	0.094301	0.024124
4. SCS		0.758780	0.090326	0.023107
8. LIB		1.000000	0.119041	0.030452
9. LAB		0.976897	0.116291	0.029749
10. VRB		0.802486	0.095529	0.024438
11. SSB		0.865789	0.103065	0.026365
12. NCB		0.862973	0.102729	0.026280
13. ZBB		0.780714	0.092937	0.023775
14. NMH		0.767772	0.091397	0.023381
15. SNC		0.792863	0.094383	0.024145

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	LAB	0,3270	0,4240	0,0971
2	LIB	0,3103	0,4239	0,1136
3	SSB	0,1065	0,2906	0,1840
4	NCB	0,0515	0,2613	0,2099
5	FS	-0,0149	0,2693	0,2843
6	SNC	-0,0194	0,2637	0,2831
7	SCS	-0,0648	0,2861	0,3509
8	NMH	-0,1334	0,1928	0,3262
9	VRB	-0,2573	0,1930	0,4504
10	ZBB	-0,3053	0,1655	0,4708

(b) Solve models with remaining 10 alternatives. In the next step, exclude SNC, ZBB, NMH, and SCS and solve.

Name	Graphic	Ideals	Normals	Raw
3. FS		0.799085	0.150012	0.038375
8. LIB		1.000000	0.187729	0.048024
9. LAB		0.982801	0.184501	0.047198
10. VRB		0.803979	0.150931	0.038610
11. SSB		0.875329	0.164325	0.042037
12. NCB		0.865620	0.162502	0.041570

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	LAB	0,2534	0,3634	0,1100
2	LIB	0,2421	0,3756	0,1334
3	SSB	0,0163	0,2392	0,2228
4	NCB	-0,0297	0,2022	0,2319
5	FS	-0,1052	0,2331	0,3383
6	VRB	-0,3769	0,1483	0,5252

(c) Solve models with remaining 6 alternatives. In the next step, exclude SSB, NCB, VRB, and FS and solve.

Name	Graphic	Ideals	Normals	Raw
8. LIB		1.000000	0.503997	0.128930
9. LAB		0.984139	0.496003	0.126885

PROMETHEE Flow Table

Rank	action	Phi	Phi+	Phi-
1	LIB	0,0032	0,1876	0,1844
2	LAB	-0,0032	0,1844	0,1876

(d) Solve models with remaining two alternatives.

Figure 16. Determination of the best storage based on AHP and PROMETHEE solutions for Case 2.

E. FUTURE OUTLOOK

Until 2050, the world is committed towards significant elimination of unsustainable generation resources from the power systems. As a result, the share of renewable energy-based power generation will rapidly increase across the whole world. In an effort to support this wonderful revolution, a large number of prosumers will actively participate in the power generation for self-consumption or sharing with other prosumers or grid [62-63]. Large scale participation of prosumers in the electricity market is an emerging trend in the developed world. However, prosumer-based power systems would fail without renewable energy storage systems [64].

Most of the recent research has focused on the utilization of batteries in prosumer-based smart grids [65-71]. Specially, PV and battery system combination is more common in the modern power systems [72]. Moreover, it has been reported that Europe will install 57 GW battery storage systems till 2030 [73]. Batteries are easily available in markets and are more compatible with prosumer-based systems. However, they have various strategic disadvantages (e.g. high cost, toxicity, short term storage, and materials scarcity) which encourage improving these batteries or searching for alternative storage technologies. This paper suggests that the batteries are the most favorable selection for prosumers.

In this paper, the lead acid and lithium-ion batteries have been selected for prosumer-based systems. The toxicity of lead acid batteries will restrict its application in the long term. Recent research is focusing on lead-free dielectric ceramics. Still, the lead-free ceramics lack practical applicability due to their lower efficiency and energy density compared with lead-based ceramics [74]. Also, scarce lithium resources cannot meet the growing storage needs of multiple prosumers. Hence, there will be several alternatives for lithium-ion batteries. For example, aqueous sodium-ion batteries are more cost effective, safe, and abundantly available compared with lithium-ion and lead-acid batteries. On the other hand, the aqueous sodium-ion batteries have some drawbacks including lower energy density and flammability. However, recent research is focusing on improving these aspects of aqueous sodium-ion batteries [75]. Despite, the aqueous aluminium-ion batteries have good energy density, good power density, more safety, and abundant availability. Recent research is working actively on the improvement of aqueous aluminium-ion batteries. In addition, magnesium, potassium, and calcium are abundantly available, and they can be considered as metal anode materials [76].

Although, the batteries seem more compatible with prosumers, they incur high investment cost and longer payback period. This fact would limit the use of batteries in the very large-scale prosumer-based power systems [77]. In the recent literature, evaluation of community storage systems is emerging for multiple prosumers. In such systems, a common storage is managed by an independent operator [78]. These community storage systems offer a common storage capacity to multiple houses [79]. A significant cost reduction and power saving have been reported for peer-to-peer energy trading systems based on community storage systems. In addition, such energy storage offers a more resilient energy future for prosumers communities [80]. These systems require battery packs containing a large number of similar or different batteries. Even a same type of battery involves different materials, manufacturing techniques, and structures, which influences the consistent operation of the large-scale battery systems. The inconsistency of battery pack would result in more faults, reduction in lifetime, and more maintenance. To overcome this issue, it has been recommended to trace the inconsistency of batteries through advanced battery management technologies [81]. A more competitive solution will be the utilization of long duration energy storage systems for the large-scale prosumer communities.

This paper has identified least preference for the large-scale non-battery storage systems including pumped hydro storage, hydrogen storage, compressed air storage, and solar thermal storage. Pumped hydro is more suitable when enough water is available at a specific place. Pumped hydro storage will be more attractive where the water storage can be ensured for a long duration. Small scale pump hydro storage will be more feasible for some prosumers. Hydrogen storage is another sustainable option. However, the application of hydrogen storage is less accepted for prosumer-based systems due to less availability in market and more overall cost [82]. Each storage technology offers unique strengths and weaknesses. Strengths of different storage technologies can be combined through the development of hybrid storage systems [83-84]. Recently, hybrid hydrogen and battery storage has been recommended for prosumer-based systems. Battery can manage the rapid and frequent power storage needs and hydrogen storage can be used for large scale storage capacity [85]. Recent research concludes that the integration of batteries with hydrogen storage can decrease the operational cost of prosumer-based power systems. However, the higher infrastructure cost of hydrogen storage results in a significant increase in overall cost. Hydrogen storage offers up to several months of energy storage compared with batteries that offer short term storage. Major cost factors in the integration of hydrogen storage into prosumer-based power systems include the additional complexity and new infrastructure requirement. The infrastructure cost of hydrogen storage techniques should be decreased through advanced technologies. In addition, innovative electrolysers should be developed which should be compatible with hybrid storage systems. Hydrogen production should be done using renewable energy resources, which will result in the reduction of air pollution, resulting in decrease of climate change risk [86]. Compressed air energy storage is another large-scale storage alternative. CAES has several major disadvantages including less energy density, less efficiency, and location dependency. Several cost-effective advancements to compressed air energy storage have been proposed, such as the use CO2 as an alternative to compressed air [87].

Prosumer based power systems will require an ideal storage system owning a range of related characteristics. Unfortunately, there is no storage system with all the required characteristics for these modern systems. Future work is required in various directions in order to enhance the storage selection decisions for prosumer-based power systems. Literature has extensively combined two different MCDM methods for different types of problems. In the literature, AHP and PROMETHEE combination is a prominent combination for multi-criteria decisions. Some papers have combined fuzzy sets with MCDM methods to increase the robustness of MCDM methods. Future work would combine MCDM with different extensions of fuzzy sets such as type-2, intuitionistic, spherical, hesitant, and Pythagorean fuzzy sets. Fuzzy sets support human judgment by decreasing vagueness and imprecision of human judgments. Recently, spherical fuzzy sets have been combined with AHP method to select the most appropriate energy storage in Egypt. The ideal storage was selected as the pumped hydro storage [88]. Future research would use this hybrid method for selecting the ideal storage system for prosumer-based power systems at various locations around the world. Reference [45] applied fuzzy logic and AHP method for storage selection amongst flywheel, supercapacitor, pumped hydro, compressed air, and hydrogen storage alternatives. In that work, the individual application of fuzzy logic and AHP method resulted in exactly the same ranking. This shows the authenticity of AHP results. However, fuzzy sets have been suggested as more reliable methods compared with AHP. Future work is required to confirm this suggestion for prosumer-based power systems. Some other methods can be used for prosumer-based power systems, such as ELECTRE, DEMATEL, TOPSIS, SAW, and ANP. Consequently, the limitations of different storage selection methods should be identified through practical implementation of different methods. Reference [89] performed energy storage selection based on fuzzy AHP and fuzzy VIKOR. Electromagnetic storage was selected as the top alternative. Fuzzy set theory has been integrated with MCDM methods for different applications. Fuzzy sets offer the integration of incomplete or inaccurate information into decision making. Reference [90] selected the compressed air storage based on the type-2 fuzzy AHP and type-2 fuzzy TOPSIS. Moreover, type-2 fuzzy AHP was used to determine the weights of criteria and the type-2 fuzzy TOPSIS was used for the selection of alternatives. Hence, a range of alternative MCDM methods can be adopted for storage selection for prosumer-based power systems.

In future, energy storage selection will remain a critical decision for efficient energy management in the prosumer-based power systems. There will be a plethora of competitive storage alternatives, and a careful selection of an ideal storage system will be an essential decision for prosumer-based power systems [91]. The inclusiveness and simplicity of a storage selection method will be the more attractive selection criteria. Prosumers have a limited time to select a comparatively more efficient technology. To select competitive storage technologies, scientific decision-making methods are very important. In this context, this paper is a substantial effort towards the implementation of two highly regarded MCDM methods, specifically AHP and PROMETHEE, for the storage selection for prosumer based smart grids. This research shows how the hybrid application of these two MCDM methods improves the reliability of results. Moreover, their robustness allows the reliable solution to a complex problem.

IV. CONCLUSION

This study successfully enhanced the storage selection decision making for prosumers in smart grids with the help of two leading MCDM methods, namely AHP and PROMETHEE. Lithium-ion battery (LIB) was found to be the best storage alternative for prosumer-based smart grids. However, lead acid battery (LAB) remained very competitive. In addition, a few other storage technologies remained competitive, which suggests that scientists would improve the specific features of these batteries. Due to the emergence of large-scale modern power systems, only LIB and LAB would not meet the substantial storage demand. In this situation, a few more storage technologies should be the focus of improvement. Which storage technologies, except LIB and LAB, would be the most promising for large scale prosumer-based complex power systems? Obviously, MCDM methods offer fair ranking based on each important criterion. At least, these MCDM methods assist us towards reliable decision making. It can be concluded that the hybridization of two different MCDM methods can tackle the storage selection problem in more systematic ways. It was found that the ranking of storage technologies was slightly different for AHP and PROMETHEE. The systematic removal of the least ranked storage technologies from both methods offered an effective and innovative decision-making method. It was also found that the combination of two methods helped in correct data entry into the respective software. It also increased the solution reliability and confidence in the decision making. Sensitivity analysis exhibited that the model solutions for AHP and PROMETHEE were very stable and robust. This work evaluated the proposed storage selection framework only in two cases due to space constraint. The proposed model is very comprehensive and flexible, which can be evaluated in numerous ways under different situations such as giving different preferences to the different main criteria and sub-criteria. The model can be evaluated with addition or removal of criteria and storage alternatives. In summary, the proposed model would substantially assist decision makers in the storage selection for prosumer-based smart grids. Future work may focus on adding a number of other MCDM methods for storage selection problems. Scientists would find more innovative ways for getting more valid and reliable results based on the hybridization of different MCDM methods. Furthermore, this paper provides future outlook on the storage selection problem, which offers future trends and research directions for the prosumer's storage selection.

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