AHP-Assisted Multi-Criteria Decision-Making Model for Planning of Microgrids

Bohra, Shabbir S. ; Anvari-Moghaddam, Amjad; Mohammadi-Ivatloo, Behnam

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Shabbir S. Bohra
Electrical Engineering Department
Sarvajanik College of Engineering & Technology
Surat, India
E-mail: bohra.shabbir@gmail.com

Amjad Anvari-Moghaddam
Department of Energy Technology
Aalborg University
Aalborg 9220, Denmark
E-mail: aam@et.aau.dk

Behnam Mohammadi-Ivatloo
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz, Iran
E-mail: bmohammadi@tabrizu.ac.ir

***Abstract*-The planning stage of any project, could it be for an industry, a commercial or energy supply system, has crucial significance and involves judicious contribution from field experts to decision makers (DM). The objective of this paper is presenting a model for planning of energy sources for microgrid using multi-criteria decision making (MCDM) based on analytic hierarchic process (AHP) approach. For developing a model, an educational institution's electrical energy load demand has been considered as reference. In this assessment, the main-utility grid as the primary source of electricity, alongside conventional sources like diesel generator (DG), gas-based combined heat-and-power (CHP) with absorption chiller to meet cooling demand of facility is taken into account. Moreover, proven and comparatively most environmentally friendly renewable energy sources, such as solar photovoltaic (PV) together with battery energy storage system (BESS) have been taken into account. Moreover, the assessment and evaluation for prioritization of energy sources based on critical criteria or attributes and their associated sub-criteria have been judged to make decision. In this model, most of the critically influencing criteria, such as economic, technical, structural, operational and maintenance, environmental and societal aspects are being focused on. In total, nine alternatives-combinations of grid and other energy source(s)-are identified to form the microgrid. The weight score for each combination of sources is computed for each of the 22 criteria and could be presented DMs to enlist priority of alternatives to choose from.**

***Keywords*- Multi-criteria decision-making (MCDM), analytic hierarchy process (AHP), energy sources, microgrid**

I. INTRODUCTION

Growing or expansion is the inevitable for survival in today's competitive world. This is applicable to not only manufacturing industries but also every player around, like energy companies, utility firms, commercial sectors, social, educational institutions or medical facility as well. The energy consumption is one of the yardsticks to define progress path of any of previously mentioned facilities towards achievement of goal. Moreover, due to depletion of fossil fuels and threatening impact on environment, certain factors should not be overlooked to win the race of progress. However, the steps adopted for progress should also be economically feasible, technically achievable, structurally endurable, environmentally sustainable and socially acceptable. Moreover, it must have enough room for expansion to meet demands for future. All these facets should be attempted to embrace the aim by a professional project planner and manager.

Any project development stage has to pass through various tangible and intangible requirements. Among others, inputs from experts are given due importance to choose the best alternative from available ones. Though, each of listed, adheres to its inherent characteristics, and thereby offering merits and demerits. In general, many a times a project selection is targeted to the most lucrative one; other option acquires selection because fulfilling majority technical requirements; whereas, a few have social and environmental attachment. Decision-making process starts with achieving an objective, second stage is collection of essential set of information, third is identification of alternatives and computing their weights incorporating all possible relevant criteria and sub-criteria of each of them. The final stage is evaluation for feasibility, acceptability and desirability to know which alternative is the best suited, weighted highest and satisfying 'ideally' all targeted criteria, which is very unlikely to happen in real life. DMs face problems when a multiple mutually conflicting objectives are to be evaluated from. The objective initially needs to be established and prioritized according to decision variables and relations among them. In an entire course of process, decision making system should be supportive to DMs in exploring and evaluating alternatives [1]. The decision-making process explained here excludes taking of action to execution of project and reviewing decision and therefore not in scope of this study. The optimal size selection of batteries as energy storage system aiming cost reduction of stored energy is also very important in microgrids [2].The role of battery energy storage systems (BESSs) in energy network and different methods, single and multi-criteria, which is preferred over former, for battery selection has been highlighted in [3]. The MCDM approach could find its niche in not only selection of the most suitable energy storage system (ESS) but also its sizing in power systems. The selection of the best plan for collaborative expansion of gas-electricity system has been introduced using MCDM with AHP in [4]. A two-stage model for optimal planning and operation of distribution system having hybrid energy sources is proposed in [5]. A multi-attribute approach has been addressed for distribution generation planning in microgrids prevailing unforeseen conditions [6].

This paper presents the assessment model for selection priority of combination of hybrid sources for given facility, could it be a residential pocket, apiece or group of commercial complexes, industry, educational institute, community or healthcare facility. An engineering academic institution located in the western part of India and its electrical load has been taken as reference to validate proposed model in this study. Present peak demand has been observed to be 125 kW and electrical energy consumption of 375,000 kWh/yr. Hybridization of energy sources for such facilities have been proposed by a number of energy conscious groups as an increasing concerned and individuals to fulfill certain criteria. The criteria could be economics, technical, social, environmental impact, sustainability or others depending on the region or country where the system is offset up. Moreover, various alternatives would be available on the market having their own pros and cons. So, most of the times, it becomes crucial to decide the best combination of energy sources fulfilling almost every single criterion to the possible extent. Because, certain sources have been found to be energy efficient and/or environmentally friendly, but in contrast to that, they may not promisingly be economical. An attempt has been made to facilitate planning of energy sources- a mix of conventional and renewable- by computing priorities of them and may turn forming a microgrid. This objective is being achieved using MCDM which is based on analytic hierarchy process (AHP) as illustrated in TABLE I.

II. IMPLEMENTATION

A. Multi-Criteria Decision-Making

The MCDM is primarily a branch of operations research (OR) wherein a problem is addressed through number of conflicting criteria or attributes; and therefore a term multi-attribute decision-making (MADM) can many a times be used in place it [7]. There are many methods, such as deterministic, stochastic and fuzzy based reported for various data types, and sometimes even combination of them. Another class of stream considers the number of DMs involved into evaluation, single or multiple DMs. Moreover, the role of DMs changes significantly depending upon nature of analysis to be carried out; could be descriptive, prescriptive or normative. In descriptive analysis, behavioral approach is the vital key component, and is mainly preferred for study of psychology, market and consumer related problems. Whereas, prescriptive and normative type of analysis should be preferred for decision-science, economics, operations research, business-product and location selection, etc. It has been surveyed that most of the real life problems are subjective [8]-[9], objective or combination of them. The decision should take into account the aim, imperative criteria or attributes, options or alternatives. The historical evidence supports the beginning of MADM during era of Nicolas Bernoulli (1687–1759) and Pierre Rémond de Montmort (1678–1719). In [10], it has been described various methods of MADM and its applications. In addition to that, numerous applications found in the field of engineering, like design analysis in integrated manufacturing, technology investment, flexible manufacturing system, layout design and others have been explained in [7]. Furthermore, he has also discussed different method to assign weights to factors. The MCDM approach has been used for designing support framework for expansion of integrated energy distribution system planning of local energy distribution system [11]. The various methods applicable to renewable energy and storage technologies have extensively been evaluated in [12]. The [13] has described various selection criteria; categorized under subjective, objective and combination of them. In addition to that, authors also discussed methods for subjective and objective weighting for sustainable energy DMs. The evolution of variety of MCDM methods and the driving motivation for selection of renewable energy sources for electricity generation has been discussed in [14] and [15]. The Prioritization of distributed generation for country of Iran has been explained in [16] using a hierarchical decision making model. The MCMD methods and their applications in electrification of rural and remote area have been studied in [17]. The planning of remote area microgrid embedding experts' opinion and MCDM has been studied in [18].

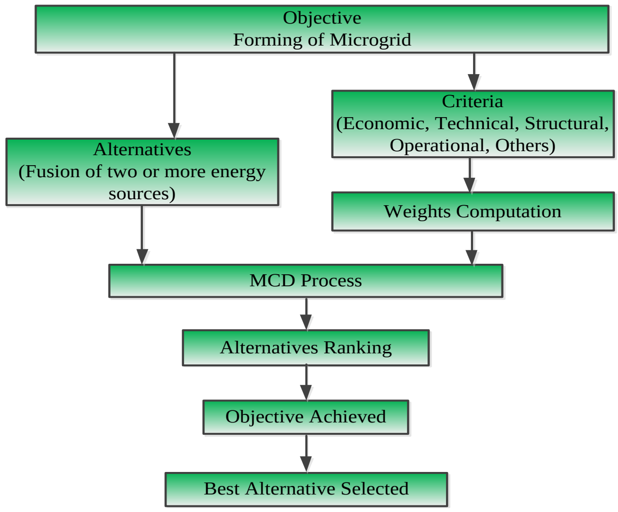


Fig. 1. Flowchart of MCDM process using AHP

B. Analytic hierarchy process (AHP)

The AHP is one of the most popular and widely used techniques for MCDM, which allows in segregating a bunch of criteria into sub-sub or -third level criteria pertaining to a particular sub (second) level criterion. Similarly, sub-criteria to certain relevant criterion (primary) making a hierarchical tree structure, which helps in distinguishing relatively impacting factors in ranking for selection of alternative. AHP helps DMs to evaluate both qualitative and quantitative criteria. The theory of AHP was given by Saaty [19] in early 90s. The AHP mainly consists of two stages: (i) determining relative weights of decision criteria and (ii) determining scores of alternatives [1],[20]. The detailed process has been shown in Fig.1 and chosen alternatives are given in TABLE II.

TABLE I. Hierarchical structure of criteria and quantitative parameter values for different energy sources

The first level hierarchical criteria	The second level hierarchical criteria	Description	Inherent nature	Typical parameter values[c]				
				UG	RTPV	BESS	DG	CHPC
Economic issues	Initial cost of investment (power capacity cost in $/kW)	Includes cost of equipment, transportation, labor, etc. except land-cost	Low	0	1750	150	500	700
	Energy cost ($/kWh)	Cost of electricity generated	Low	0.084	0.0008	0.0075	0.28	0.2380
	Operational and maintenance cost ($)	The cost of maintenance and repair in case of breakdown and to uphold unit output at rated value	Low	1.0	0.5	0.5	0.75	1.0
	Estimated internal rate of return (IRR) (%)	It is a discount rate, which makes the net present value (NPV) of all cash flows from a particular project equal to zero.	High	-	7.6	10.3	5.7	2.39
Structural issues	Footprint (m^3/kW or m^2/kW)	The space required for installation of unit, e.g. roof area for Solar Rooftop PV system or an open/closed space for BESS/DG/CHP	Low	0.2	2.0	0.015	2.5	3.0
	Life time(years)	Years unit will remain operative satisfactorily without major unforeseen shut-downs	High	100	25	6	20	15
	Modularity (1 for highly modular and 0 for non-modularity)	Important for future expansion with existing or updated technology	High	0	1.0	0.5	0.25	0
	Installation lead time (months)	It is the latency between the commencement and execution of a process	Low	0	1.0	1.0	3.0	6.0
	Annual performance degradation (% of rated power)	Every system degrades after usage due to aging but should not have steep fall in performance as percentage of rated power	Low	0	0.75	2.5	1.5	1.25
Technical issues	In-house or local technical skill requirement (1-for specially skilled and 0-for unskilled)	During regular maintenance and shutdown, local personal should be able to fix the issue	Low	0.1	0.1	0.2	0.5	0.7
	Self-sustainability or islanding feature(1- for most to 0-least capable of)	It is the capability of unit to work in unison with and even in absence of macro or main grid	High	0	1.0	0.7	1.0	0.8
	Availability of fuel (1-for nearby/easily accessible and 0-for scarcity in vicinity)	If a unit requires fuel- fossil or renewable- but should be available readily in moderate vicinity	High	0	0	0	0.9	0.7
	Generation capacity (kW)	Expected to have at least 25% of maximum demand of given facility to fulfill islanding feature	High	125	50	25	25	25
Operation issues	Efficiency (%)	Ratio of output power (kW) to input power (kW)	High	100 [a]	16.5	90.0	35.0	40.0
	Operational days per year	Should have minimum downtime due to maintenance and be least affected by other factors, like sunshine, wind, temperature, etc.	High	365	300	300	60	200
	Estimated energy production (kWh)	Unit should generate as maximum as possible electrical energy	High	-	82,500	10,000	12,500	17,500
	Forced outage rate(FOR)/ reliability(on scale of 1for highest-to-0 for least)	The duration of time a unit is in demand, but is unavailable due to forced outages, de-ratings, scheduled maintenance or repair/failure.	Low	0.95	0.6	0.5	5.5	3.5
	Capacity utilization factor(CUF)	It is the ratio of the actual output from a unit over the year to the maximum possible output from it for a year under ideal conditions.	High	1.0	18.5	30	45	60
Others (environmental, societal issues and stakeholders' preference)	Noise (at 3 mt. distance in db)	Factor which impacts the human being working around, and has great importance when installed unit is in vicinity of educational, medical, holy places	Low	0	0	0	75	85
	CO_2emission of Pollution[b] (kg/MWh)	The most major green-house-gas GHG and increase at alarming rate and needs special attention	Low	130	8.92	26.87	76160	55560
	Aesthetics/elevation (1-for better and 0-for poor look)	Installation of unit may spoil look of a building, premises and is important for aesthetically designed structures.	High	1	0.9	0.8	0.5	0.75
	Stakeholders preference	The opinion of a group of people involved directly or indirectly matters.	High	10	7	5	3	4

[a] efficiency of grid connected system is assumed to be the highest and power loss in substation equipment has been neglected due to trivial reason

[b] CO_2 emission is being calculated for diesel as primary fuel used for production equipments as DG is one of the electricity sources considered

[c] average realistic parameter values have been considered as it depends on size, construction, material, and other factors after referring manufactures' details and datasheets

Preparing pair-wise comparison matrix is the very first step in AHP. The elements of this matrix $\mathbf{A}_{mxm}=[a_{ij}]$,where, a_{ij} represents the importance of the i^{th} criterion relative to the j^{th} one. The deciding scale was proposed by Saaty[20] and taken as reference in this assessment. If the i^{th} criterion is more important than j^{th} then $a_{ij}>1$; $a_{ij}=1$ for having equal importance and $a_{ij}<1$,if criterion j^{th} is relatively more significant than i^{th}. This obviously makes $a_{ij}\cdot a_{ji}=1$ *and* $a_{ii}=a_{jj}=1$.

TABLE II. Different Alternatives as Group of Resources Blended with Main-Utility Grid

Sr. No.	Alternatives[a]
1	UG + RSPV
2	UG + BESS
3	UG + DG
4	UG + CHPC
5	UG + (PV+BESS)
6	UG + (PV+DG)
7	UG + (PV+CHPC)
8	UG + (PV+BESS+DG)
9	UG + (PV+BESS+CHPC)

[a] Utility grid (UG),rooftop solar photovoltaic (RSPV), battery energy storage system (BESS), diesel generator (DG), combined heat and power with absorption chiller (CHPC)

C. Computing of criteria weight vectors

The relative importance between criteria is ranked between 1-to-9, the scale was suggested by Saaty [20] is depicted in TABLE III.

TABLE III. The fundamental scale of Saaty for deciding relative importance

Intensity of importance on a fixed scale	Description
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extremely strong importance
2,4,6,8	Intermediate values between two adjacent decisions

The normalized pair-wise matrix $\mathbf{A}_{norm}$ is obtained using the following:

$$\overline{a_{ij}} = a_{ij} \Big/ \sum_{i=1}^{m} a_{ij} \tag{1}$$

where, m indicates number of evaluated criteria/sub-criteria to be compared. Then after, criteria weight vector w, which is k-dimensional column vector is computed taking mean of each row of $\mathbf{A}_{norm}$ as per (2).

$$w_i = \left(\sum_{i=1}^{k} \overline{a_{ij}} \right) / k \tag{2}$$

Let the j^{th} entry of the i^{th} criterion is being compared with the l^{th} of the same criterion and assuming values for the same criterion lie in the interval of $[I_{j,max}, I_{j,min}]$. Therefore, the assignment of scaling as per aforementioned rules, *i.e.* assigning weights between 1-to-9 has been computed using following expression in order to make process semi-automated for objective criteria:

$$a_{ij} = 8 \cdot \frac{I^{j} - I^{l}}{I_{j,\max} - I_{j,\min}} + 1 \tag{3}$$

where, $I_j \geq I_j'$ and larger value of criterion is an indication of higher possibility acceptance by DMs. On the other, if smaller value is preferred for criterion, then its reciprocal should be considered.

TABLE IV. Pair-wise comparison- scale and normalized

Criteria	Economic	Operational	Structural	Technical	Others
Economic	1 (0.15)	3 (0.44)	3(0.3214)	0.33(0.0645)	0.5(0.071)
Operational	0.33(0.05)	1(0.146)	3(0.321)	0.5(0.097)	2(0.286)
Structural	0.33(0.05)	0.33(0.049)	1(0.107)	3(0.581)	0.5(0.071)
Technical	3(0.45)	2(0.293)	0.33(0.036)	1(0.194)	3(0.429)
Others	2(0.3)	0.5(0.073)	2(0.214)	0.33(0.065)	1(0.143)
Sum	6.67	6.83	9.33	5.17	7

Values in bracket indicate normalized values

D. Consistency Check

In AHP the priority of alternatives are decided from consistency of matrices and can be measured by consistency index (*CI*) [21] as given in following:

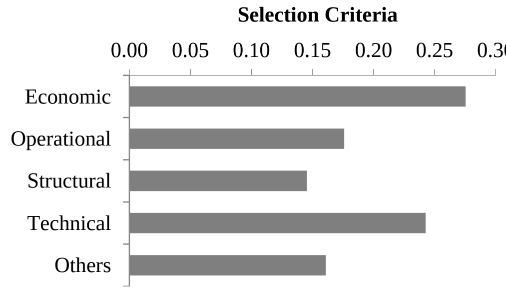
$$CI = \frac{\lambda_{\max} - m}{m-1} \tag{4}$$

where, λ_{max} is the sum of product of associated weight and sum of respective column of pair-wise comparison. The competency of *CI* can be validated by determining randomized (consistency) index (*RI*), the average *CI* for randomly filled matrices. The consistency ratio (*CR*) can be calculated as below:

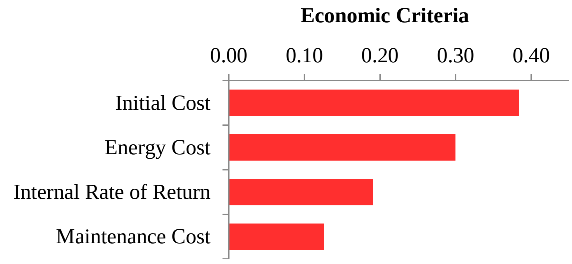
$$CR = \frac{CI}{RI} \tag{5}$$

where, *RI* can be obtained using $\overline{\lambda}_{\max}$ [21]:

$$RI = \frac{\overline{\lambda}_{\max} - m}{m-1} \tag{6}$$



(a)



(b)

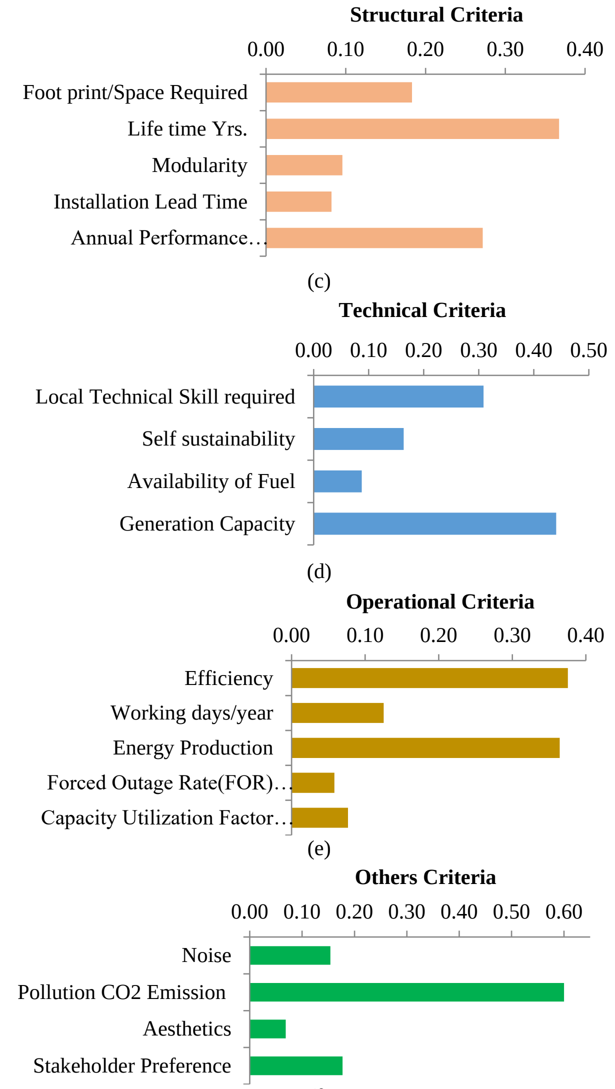


Fig.2. Weight vectors for criteria and sub-criteria (priority order is economic, technical, operational, structural and least to others)

III. DESCRIPTION OF WEIGHTS AND COMPUTATION

In this study, the economical perspective is assumed to be of primary concern of DMs, which is quite usual in most of projects. There is always a trade-off between economical and technical attributes and prioritizing them that makes DMs perplexed. However, here technical is regarded as the second position over expenditure Fig. 2(a). For small premises, reserving space for expansion and prolonged life span have always been significant issues and hence is followed by operational aspects which is reflected to be of more important. The other criterion, which is a group of indirectly tangible facets of project, like noise and air pollution, impacts on society and stakeholders' opinion as illustrated in TABLE I. The DMs may not be uncertain or unfamiliar about pollution emitted by new unit(s), unless the regional or national norms are enforced to do so. Noise level may not be so perceptible for larger area and overlooked. Furthermore, lacking active involvement and/or unawareness about project and available alternatives to stakeholders could also be one of the reasons for being least important over other criteria. Contradictorily, it also happens that DMs are more rational about environment and give highest priority to it. In addition, DMs may wish to have state-of-the-art technology to achieve the goal and inherently structural and technical criteria will be satisfied without much efforts, which is depicted in Fig. 3.

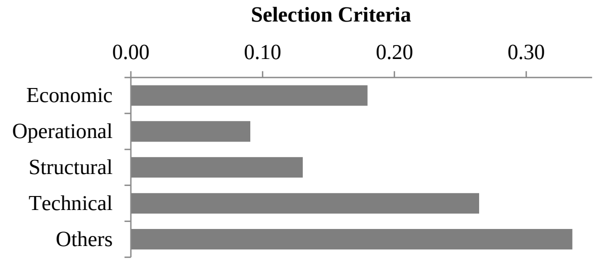


Fig.3. Weight vectors for primary criteria (others are more important)

TABLE V. Consistency of first-level criteria

Sr. No.	Name of Sub-Criteria	CI	RI	CR (<0.1 for better consistency)
1	Economic	0.054	0.909	0.06
2	Structural	0.046	1.125	0.041
3	Technical	0.042	0.909	0.046
4	Operational	0.097	1.125	0.086
5	Others	0.084	0.909	0.092
6	Overall Criteria	0.095	1.125	0.085

In majority, estimated initial investment plays pivotal role to frame mindset of DMs. Hence, initial cost is given higher weight before energy cost. It actually reflects indirect saving from the project, although. IRR and maintenance cost are at almost same weight as can be seen from Fig.2(b).

For structural criteria, investors do not wish to go for replacement or major retrofitting in existing units after no less than few years after commissioning to meet future requirements and is the reason for highest weight assigned to lifetime of system over other sub-criteria Fig.2(c).

Higher installed generation capacity, followed by the local skill requirement in case of breakdown, repair and regular maintenance, self-sustainability during unavailability of main grid and availability of fuel in near vicinity are the sub-criteria for technical criterion in given order of priority Fig.2(d).

Efficiency and energy production are of equal significance in operation criteria over number of days unit(s) remains operational throughout a year Fig.2(e).

The nature of facility demands certain conformity of appearance; could it be academic or research institute, social, community, regional, commercial or industrial premises. Every class has its own preference and needs and accordingly weight could be assigned Fig.2(f).

After computing all the priorities and consistency ratios, the relative weight of each alternative for each criterion has been calculated to evaluate weights of all the alternatives. Firstly, the weight of each sub-criterion is multiplied with the weight of corresponding criterion, *e.g.* the weight of initial cost sub-criterion is 0.3838 and weight of economic criterion is 0.2753. Therefore, global priority weight for initial cost becomes 0.1057. The weight of each alternative could easily be made available after preparing pair-wise comparison for objective type of criteria for each alternative, *e.g.* for combined grid-PV alternative, it is 0.0376. Now, this weight has to be multiplied with respective global priority weight, which is 0.1057 as aforementioned to decide the overall position of given alternative, which is 0.1357. Similarly, for all nine alternatives are assigned weights for all twenty-two sub-criteria for this planning project and its sum should be verified for unity. The final weights of alternatives are illustrated in Fig.4.

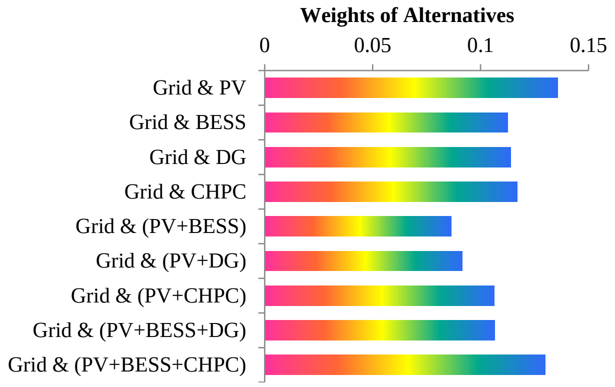


Fig. 4. Weights of energy sources as alternatives

IV. CONCLUSIONS

The trend has taken a turn from macro/utility grid to formation of microgrid due to its inevitable advantages, like scope of local expansion, islanding feature for sensitive loads and sustainable operation during interruptions. In this paper, the efforts have been made to simplify human cognitive approach of DMs for selection of the best alternative, a combination of two or more energy sources for given facility. This has been evaluated with the help of AHP-assisted MCDM approach since such process includes number of multiple mutually confronting and interdependent parameters. After evaluation, it has been found that for given set of preferences and parameters, the highest score is assigned to grid-PV (0.136) followed by grid-PV-BESS-CHPC (0.130). The other alternatives with grid like BESS, DG, CHPC, PV-CHPC, PV-BESS-DG have scored between 0.1 to 0.12 except grid-PV-BESS and grid-PV-DG (which have scores less than 0.1 and hence least suitable candidates for such project planning and given parameters). In this study, total 22 sub-criteria belonging to various five primary criteria have been taken into account to decide weight score of each alternative. Though, almost all sensitive criteria which are found to be crucial in selection of energy sources for flawless planning have been taken care of in this work, but DMs may choose more or less criteria depending on demand and vision of expansion and planning. Moreover, if one (more) parameter(s) changes dramatically, it may likely to change the priority of alternatives and therefore, this model could be versatile for selection any kind of energy source or sources, provided genuine inputs from experts and objective to be fulfilled. Variation in cost of manufacturing, advancement in technology, environmental norms will affect the weight of alternatives due to dependent nature.

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