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Design of 3-phase Static Modular Double-conversion Lithium-ion-based UPS System

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Abstract A challenge for industries nowadays is to optimize the functionality of their critical processes. Whether they be manufacturing, production, healthcare, banking, data, research, or shopping centres, they are becoming large and complex with several critical loads and processes whose availability is crucial to their overall effectiveness and market competitiveness. Based on their design specifications and accuracies expected, these processes often tend to have a low tolerance and are susceptible to power failures, spikes, brown-out, dip, or surges. They require a high integrity power supply to guarantee their correct functioning, increase their robustness against the damaging effect of power disturbances and operational availability. Eskom's network instability, lower energy availability, and poor power quality, unfortunately, cannot guarantee the integrity of supply to these critical loads. An increase in load shedding in the past few years highlights this low energy availability factor. Based on these reasons, the facility opted to install 4 x 1100kVA online lead-acid-based rotary UPSs to sustain a sturdy power supply through periods of power disturbances. The sustainability of power will also allow orderly processes shutdown in case of prolonged power interruption and avoid any outage-related financial setbacks. Commissioned back in 1995, they have attained their end-of-life and suffer regular costly maintenances, higher losses, and higher spares cost due to unavailability. Although these are considered legitimate running costs, they occur on a capital scale after few years. Given the system's age, running cost, and inefficiency, the facility would be efficiently and cost-effectively served by newer high-performance UPS systems. The process of choosing the right UPS system and energy storage solution for critical infrastructure has now become more challenging than ever. Today's UPS technologies and their corresponding backup storage solution must maintain or even increase the availability and manageability of power on their respective facilities. In the effort to reduce the total cost of ownership, it is imperative to extend lifetime, decrease footprint, streamline maintenance, and lower cooling costs and other operating expenses, in addition to reducing the upfront capital investment. Lithium-ion-based static UPS systems are poised to enhance energy storage for secure power applications. They provide benefits in reducing the installation and maintenance costs and have low waste energy resources making them have high operational efficiency and weigh less than the rotary UPS system. The energy storage system used in these systems has since transformed from medium-lifetime, sprawling, and heavy lead-acid batteries to a long-life, compact, lightweight solution with predictable performance, simplified maintenance, and robust life cycle management. The intervention strategy will present a comprehensive assessment that offers a site-specific solution. It will also provide a financial and performance analysis of the current rotary UPS system versus the new static UPS system with the desire to improve the facility's power protection, secure its long-term availability, strengthen its energy efficiency capacity, and reduce maintenance costs and carbon footprint.

Keywords Floor loading capacity, Power and usable energy density, Spatial footprint, Storage capacity, Total cost of ownership

1. Introduction

Several papers have elaborated on the beneficial effects in evaluating the UPS efficiency, losses effects, power density, spatial footprint requirement, and floor loading of various power systems between static UPS (SUPS) and rotary UPS (RUPS) systems. Several others have provided some framework that guides users' decisions into selecting the best UPS type to be deployed while basing these decisions on their specific circumstances and requirements. A couple of battery technologies have since developed into commercially worthwhile alternatives to lead-acid technology; amongst these technologies is the lithium-ion technology. Several other papers have elaborated on the comparative analysis between lithium-ion and lead-acid batteries (LIBs and LABs) for UPSs and various applications. They have included

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the baselines to be considered for optimal chemistry and technology selection suitable to the application [4,5,14,18,19,21,25]. Unfortunately, this evaluation, selection process, comparison, or decision elaboration process cannot fit aspects of all facilities; these aspects are situational, site-specific, and subject to requirements imposed by their power system and protection security.

The energy analysis of any UPS system is always associated with costs. The examination and assessment of only its operational electrical energy wasted can approximately determine these costs. Being linked to a volatile tariff price adjustment administered by Eskom for the past ten years, these costs will increase as the energy tariff increases. It is important to note that the 2020/2021 tariff price adjustment previously predicted is no longer valid following the affirmation of an average tariff increase of 15.06% in the 2021/22 financial year [12]. However, where an optional UPS system is available, it is always necessary to compare its performance with the existing system. The establishment of how optimal and cost-effective the current UPS system is vis-à-vis the new system is done by first determining their wasted energy costs separately and then comparatively assessing them.

These data are crucial in fully informed decision-making, capital expenditure budget motivation, determination of their economic competitiveness, and how quickly they repay the capital investment injected into them.

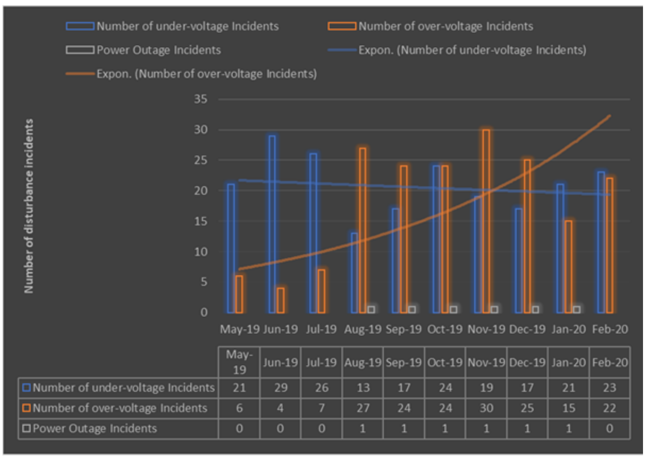
From a design perspective, the capacity of a UPS system links to its physical size. For various UPS products, these dimension specifications are often available in the catalogues and manufacture' manuals. Although that is the case, there is no single source where these data are summarised comparatively for every product due to information limitations or lack of motive to conduct such comparison. Inside the wide range of UPS technologies presently available in the market, over and above the enhancement in power rating, modularity, redundancy, and efficiency, the compactness of their components has since drastically improved through the use of high-frequency and high-power IGBT semiconductors. This featuring characteristic drove their footprint and weight down when compared with traditional lead-acid-based RUPS systems (LAB-RUPSs). Although the spatial area, weight, and consequently the power density of a new generation UPS system is most likely to be lower than that of the legacy UPS system, the evaluation to confirming and proving this hypothesis is, anyway, needed. This assessment will also determine the impact the system will have on its initial installation cost, land need, civil and structural works, and infrastructure loading requirements. It is also worth mentioning that the correlation between the UPS system's capacity and space they occupy and the physical load exerted on structures where they are mounted forms a significant aspect of their market sustainability and appraisal. It is only for these reasons that power density (kW/m^2) assessment becomes an important metric in fully informed decision-making, selection, and budget motivation.

The most vital section of the UPS system is its energy storage system that delivers the required energy to guarantee continuous conditioned power feed to critical loads or processes. This statement leads to say a UPS system is only as good as its battery energy storage system (BESS). The sizing of a BESS for a specific application is per the required facility's power capacity, autonomy duration, power storage capacity, battery depth of discharge, battery efficiency, UPS efficiency, UPS power factor, and design efficiency. These aspects are situational and subject to requirements imposed by the type of system employed and the facility's power protection requirements. The evaluation of usable energy density and storage capacity among selected BESSs conducted across different facilities' power reticulations will, therefore, meant to differ. While the development of the lithium-ion battery chemistries gains paces every day intending to enhance and optimize their performances, analysis in the understanding of the current battery technology against developed technologies is key to proving the efficacy of the future facility's power protection system. Even though the operational performances, usable energy density, and storage capacity of a new generation battery chemistry system are most likely to be higher than a legacy battery system, those aspects should, anyway, be evaluated and confirmed. Furthermore, the relationship between BESSs' stored energy capacity and the constant discharge power delivered when called upon forms a significant aspect of their market sustainability and appraisal. The assessment of this aspect is significant to the determination of the amount of power is stored in each BESS bank to be drawn from when needed and clarification of the impact the BESS will have on the facility's power protection security during low power qualify periods. Based on that, energy density assessment has become a very useful metric in fully informed decision-making, selection, budget motivation, and determination of performance competitiveness.

Overall, this paper will use a specific facility-based approach to evaluate various benefits and characteristics between the old LAB-RUPS and the new LIB-SUPS system. This evaluation will conclude in three stages. The first stage will be to represent a comprehensive approach to saving energy, promote and implement an energy management system and energy system optimization that strengthens facility capacity in energy efficiency and carbon dioxide emissions reduction aligned with SANS/ISO 50001. The second stage will be to provide a statistical summary from the evaluation of power density and floor loading capacity associated with the deployment of the new lithium-ion-based SUPS (LIB-SUPS) following the replacement of an old LAB-RUPS. The third stage is where the overall UPS+BESS spatial footprint, the floor loading capacity, and the usable energy density and storage capacity of BESSs associated with UPS systems are comparatively assessed on a common basis to identify and establish if the system selected is optimum and economical.

1.1. Background and Problem Statement

There are several modern electronic types of equipment used by the facility. Based on their design specifications and accuracies expected, a high integrity power supply to increase their robustness against the damaging effect of power disturbances, as illustrated in Figure 1, is needed. Unfortunately, Eskom's network instability, lower energy availability, and poor power quality factors cannot guarantee the required integrity of the supply [6,26]. If the facility had to depend solely on the power utility, these unconditioned disturbances will negatively impact its key processes and affect production capacity. Following an analysis of energy used by critical systems, a 4 x 1100kVA online LAB-RUPSs system has been installed. The UPS system was commissioned back in 1995 with an autonomy of 15 minutes. It now poses major operational threats such that the potential failure of these UPS units will remove power protection security, increase the susceptibility to equipment damage, and severely disrupt production. The recovery time from power interruptions will significantly increase since various systems placed in cold start conditions might take up to a day to complete their setup [18,19].



	May-19	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20	Feb-20
Number of under-voltage Incidents	21	29	26	13	17	24	19	17	21	23
Number of over-voltage Incidents	6	4	7	27	24	24	30	25	15	22
Power Outage Incidents	0	0	0	1	1	1	1	1	1	0

Figure 1. Facility energy disturbances

The current situation necessitates an investigation of the alternative backup source to lower protection threats posed, total operational energy losses and costs, and decrease the carbon footprint. This journal paper will address these threats and consequences, determine a viable option to mitigate this situation, and secure the long-term availability of conditioned power by replacing the existing system with a modern system of equivalent capacity. The address will provide a financial and practical analysis of the current LAB-RUPS system versus the modern system with the desire to cost-effectively improve power protection, backup time, power quality, and efficiency. The planning intervention strategy that integrates or retrofits components of the new system into the existing building space is required. A representation of a comprehensive approach to saving energy through system technology change that promotes and implements energy management and optimization that strengthens the facility's capacity in energy efficiency and carbon footprint reduction is as well required. The feasibility study in this journal paper will break into three main stages, namely, the inception of the current RUPS system, the conceptualization of the new SUPS system, and the comparative analysis.

2. UPS System Feasibility Study

2.1. Inception of the Current RUPS System

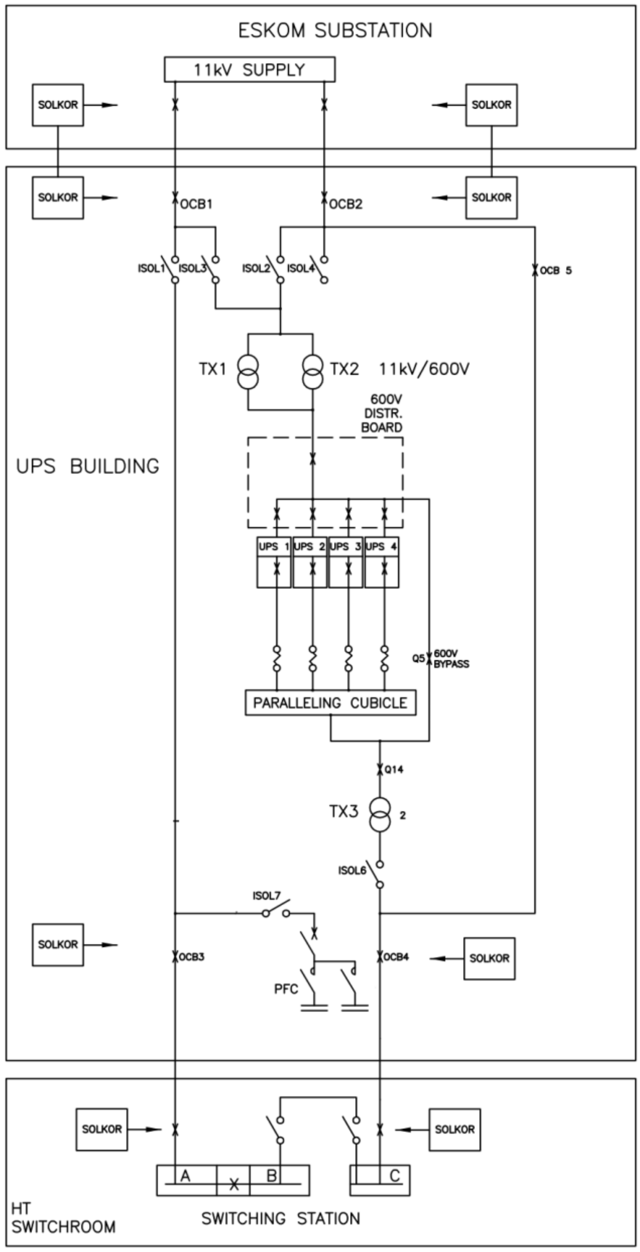


Figure 2.1. Facility MV reticulation

The site is supplied by the local authority from a 66/11kV substation as shown in Figure 2.1 with a 5MVA notified maximum demand. All 4 x 1100kVA RUPS units supply a common output bus inside the paralleling cubicle. Through the operator selection, they can run either in the power rating or redundant parallel mode. If an uncorrectable power imbalance occurs in one set or if one RUPS fails, the system will switch automatically to external bypass mode by opening the 600V bypass breaker Q5. For UPSs' maintenance breaker Q5 is used to bypass the critical loads. And for either transformers or UPSs' maintenance breaker OCB5 is used.

2.1.1. RUPS Footprint and Floor Loading Capacity

RUPS width x depth x height = 5.16 x 1.32 x 2.265m
The area occupied by each UPS = 5.16 x 1.32 = 6.8112m^2
The area occupied by all UPSs = 6.8112 x 4 = 27.245m^2
Input cabinet weight = 2475kg
Output cabinet weight = 1320kg
Motor-Generator set weight = 7600kg
Accessories weight = 240kg
Silencer weight = 255kg
Complete system weight = 11890kg
The total weight of all UPSs = 11890 x 4 = 47560kg

2.1.2. Lead-acid BESS (LA-BESS) Rating

An important consideration related to the sizing and selection of an appropriate BESS suitable for a given UPS application is its rated power and self-sufficiency period at various load rates following the analysis of the facility's energy usage of critical equipment. The amount of electrical power to be considered is the power delivered by that BESS when called upon ($P_{bat\text{-}UPS}$). For that reason, the calculation of the BESS rating will start with the UPS apparent power required to support critical loads (S) while also considering the overall UPS system efficiency (η_{UPS}) and power factor ($cos\varphi$) as per Equation 2.1 below:

$$P_{bat\text{-}UPS} = \frac{S \times cos\varphi}{\eta_{UPS}} \quad (2.1)$$

The most salient approach in determining the size of the BESS is to bring up its project planning datasheet. This project planning datasheet details the battery performance data (constant discharge power and current) based on its autonomy time under various load rates and at a predetermined operating temperature and end-of-discharge. It is imperative to ensure uniformity of battery type throughout the battery storage system.

Table 2.1. Constant Battery Discharge Current [2]

BAE Secura OGi PROJECT PLANNING DATA Page 9 from 14

Uf = 1,8 V/Cell — Discharge current in A

Battery	1'	3'	5'	6'	7'	8'	9'	10'	15'	20'	25'	30'	40'	45'	50'	55'	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h
5 OGi 400	445	445	445	445	445	445	444	435	393	360	334	312	276	261	247	234	223	141	104	83	71	61	54	49	45	42
6 OGi 480	524	524	524	524	524	524	523	513	463	424	393	367	325	308	291	276	262	166	122	98	83	72	64	58	53	49
7 OGi 560	600	600	600	600	600	600	599	587	530	486	450	420	372	352	333	316	300	190	140	112	95	83	73	66	61	56
8 OGi 640	673	673	673	673	673	673	671	658	594	545	505	471	418	395	373	354	337	213	157	126	107	93	82	74	68	63
9 OGi 720	742	742	742	742	742	742	741	725	655	601	556	519	461	436	412	390	371	235	173	139	118	102	91	82	75	69
10 OGi 800	891	891	891	891	891	891	889	870	786	721	668	623	553	523	494	469	446	282	208	167	141	122	109	99	90	83
11 OGi 880	971	971	971	971	971	971	969	949	857	786	728	679	602	570	539	511	486	307	226	182	154	133	119	107	98	91
12 OGi 960	1049	1049	1049	1049	1049	1049	1047	1025	926	849	786	734	651	616	582	552	525	332	245	196	166	144	128	116	106	98
13 OGi 1040	1126	1126	1126	1126	1126	1126	1123	1100	994	911	844	788	698	661	625	592	563	356	262	211	178	155	138	125	114	105
14 OGi 1120	1201	1201	1201	1201	1201	1201	1198	1174	1060	972	900	840	745	705	666	632	601	380	280	225	190	165	147	133	122	112
15 OGi 1200	1274	1274	1274	1274	1274	1274	1271	1245	1125	1031	955	892	791	748	707	670	638	403	297	239	202	175	156	141	129	119
16 OGi 1280	1346	1346	1346	1346	1346	1346	1343	1315	1188	1089	1009	942	835	790	747	708	674	426	314	252	213	185	165	149	136	126
17 OGi 1360	1416	1416	1416	1416	1416	1416	1413	1384	1250	1146	1062	991	879	831	786	745	709	448	330	265	225	195	173	157	143	132
18 OGi 1440	1484	1484	1484	1484	1484	1484	1481	1451	1310	1201	1113	1039	921	871	824	781	743	469	346	278	235	204	182	164	150	139
19 OGi 1520	1692	1692	1692	1692	1692	1692	1689	1654	1494	1370	1269	1184	1050	993	939	890	847	535	394	317	268	233	207	187	171	158
20 OGi 1600	1769	1769	1769	1769	1769	1769	1765	1729	1562	1432	1326	1238	1098	1039	982	931	885	559	412	331	281	243	217	196	179	165
21 OGi 1680	1845	1845	1845	1845	1845	1845	1841	1803	1629	1493	1383	1291	1145	1083	1024	971	923	583	430	346	293	254	226	204	187	173
22 OGi 1760	1920	1920	1920	1920	1920	1920	1916	1876	1695	1554	1439	1344	1191	1127	1065	1010	961	607	447	359	304	264	235	213	195	180
23 OGi 1840	1993	1993	1993	1993	1993	1993	1989	1948	1760	1613	1494	1395	1237	1170	1106	1049	998	630	465	373	316	274	244	221	202	186
24 OGi 1920	2065	2065	2065	2065	2065	2065	2061	2019	1823	1672	1549	1446	1282	1212	1146	1087	1034	653	481	387	327	284	253	229	209	193
25 OGi 2000	2137	2137	2137	2137	2137	2137	2132	2088	1886	1729	1602	1495	1326	1254	1185	1124	1069	676	498	400	339	294	261	237	217	200
26 OGi 2080	2206	2206	2206	2206	2206	2206	2202	2156	1948	1786	1654	1544	1369	1295	1224	1161	1104	698	514	413	350	303	270	244	224	206
27 OGi 2160	2275	2275	2275	2275	2275	2275	2270	2224	2008	1841	1706	1592	1412	1336	1262	1197	1139	719	530	426	361	313	278	252	231	213
28 OGi 2240	2343	2343	2343	2343	2343	2343	2338	2290	2068	1896	1756	1640	1454	1375	1300	1232	1172	741	546	439	371	322	287	259	237	219
29 OGi 2320	2409	2409	2409	2409	2409	2409	2404	2354	2126	1950	1806	1686	1495	1414	1337	1267	1205	762	562	451	382	331	295	267	244	225
30 OGi 2400	2474	2474	2474	2474	2474	2474	2469	2418	2184	2002	1855	1731	1535	1452	1373	1301	1238	782	577	463	392	340	303	274	251	231

Temperature: 25°C 12.02.2004
OGi cell_Amps 25 degC_00

ENERGY FROM BATTERIES

BAE

Table 2.2. Constant Battery Discharge Power [2]

BAE *Secura OGi* **PROJECT PLANNING DATA** Page 9 from 14 BA11

Uf = 1,8 V/Cell — Discharge power in W

Battery	1'	3'	5'	6'	7'	8'	9'	10'	15'	20'	25'	30'	40'	45'	50'	55'	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h
5 OGi 400	806	806	806	806	806	806	806	790	720	664	618	579	516	489	463	440	419	267	198	159	135	118	105	96	88	82
6 OGi 480	950	950	950	950	950	950	949	931	848	782	728	682	608	575	546	519	494	315	233	187	159	139	124	113	104	96
7 OGi 560	1087	1087	1087	1087	1087	1087	1087	1066	971	895	833	781	696	659	624	594	565	360	266	214	182	159	142	129	119	110
8 OGi 640	1219	1219	1219	1219	1219	1219	1218	1194	1088	1004	934	875	780	738	700	665	634	404	298	240	204	178	159	145	133	124
9 OGi 720	1344	1344	1344	1344	1344	1344	1343	1317	1200	1107	1030	965	860	814	772	734	699	445	329	265	226	196	176	160	147	136
10 OGi 800	1613	1613	1613	1613	1613	1613	1612	1581	1440	1328	1236	1158	1032	977	926	881	839	534	395	318	271	235	211	192	176	164
11 OGi 880	1758	1758	1758	1758	1758	1758	1757	1723	1570	1448	1347	1262	1125	1065	1010	960	914	582	430	347	295	257	230	209	192	178
12 OGi 960	1900	1900	1900	1900	1900	1900	1899	1862	1697	1565	1456	1364	1216	1151	1091	1037	988	629	465	375	319	277	248	226	208	193
13 OGi 1040	2038	2038	2038	2038	2038	2038	2038	1998	1821	1679	1562	1464	1304	1235	1171	1113	1060	675	499	402	342	297	266	242	223	207
14 OGi 1120	2174	2174	2174	2174	2174	2174	2173	2131	1942	1791	1666	1561	1391	1317	1249	1187	1131	720	533	429	365	317	284	258	238	220
15 OGi 1200	2307	2307	2307	2307	2307	2307	2306	2261	2061	1900	1768	1657	1476	1398	1325	1260	1200	764	565	455	387	337	301	274	252	234
16 OGi 1280	2437	2437	2437	2437	2437	2437	2436	2389	2177	2007	1868	1750	1560	1477	1400	1331	1267	807	597	481	409	356	318	289	266	247
17 OGi 1360	2564	2564	2564	2564	2564	2564	2563	2513	2290	2112	1965	1841	1641	1554	1473	1400	1333	849	628	506	430	374	335	304	280	260
18 OGi 1440	2688	2688	2688	2688	2688	2688	2687	2635	2401	2214	2060	1930	1720	1629	1544	1468	1398	890	658	530	451	392	351	319	294	273
19 OGi 1520	3064	3064	3064	3064	3064	3064	3063	3003	2737	2524	2348	2201	1961	1857	1760	1673	1594	1015	751	604	514	447	400	364	335	311
20 OGi 1600	3204	3204	3204	3204	3204	3204	3203	3140	2862	2639	2455	2301	2050	1941	1840	1749	1666	1061	785	632	538	468	418	380	350	325
21 OGi 1680	3341	3341	3341	3341	3341	3341	3340	3275	2984	2752	2561	2400	2138	2024	1919	1824	1738	1107	818	659	561	488	436	397	365	339
22 OGi 1760	3476	3476	3476	3476	3476	3476	3475	3407	3105	2864	2664	2497	2225	2106	1997	1898	1808	1152	851	686	583	507	454	413	380	353
23 OGi 1840	3609	3609	3609	3609	3609	3609	3608	3538	3224	2973	2766	2592	2310	2187	2073	1971	1877	1196	884	712	606	527	471	429	395	366
24 OGi 1920	3740	3740	3740	3740	3740	3740	3739	3666	3341	3081	2866	2686	2393	2266	2149	2042	1945	1239	916	738	628	546	489	444	409	379
25 OGi 2000	3869	3869	3869	3869	3869	3869	3868	3792	3456	3187	2965	2779	2476	2344	2223	2112	2012	1282	948	763	649	565	505	459	423	392
26 OGi 2080	3996	3996	3996	3996	3996	3996	3994	3916	3569	3291	3062	2869	2557	2421	2295	2181	2078	1324	979	788	670	583	522	474	437	405
27 OGi 2160	4120	4120	4120	4120	4120	4120	4118	4038	3680	3394	3157	2959	2636	2496	2367	2249	2143	1365	1009	813	691	601	538	489	450	418
28 OGi 2240	4242	4242	4242	4242	4242	4242	4240	4158	3789	3494	3251	3046	2715	2570	2437	2316	2206	1405	1039	837	712	619	554	504	464	430
29 OGi 2320	4362	4362	4362	4362	4362	4362	4360	4275	3896	3593	3343	3133	2791	2643	2506	2382	2268	1445	1068	860	732	637	570	518	477	442
30 OGi 2400	4480	4480	4480	4480	4480	4480	4478	4391	4001	3690	3433	3217	2867	2714	2573	2446	2330	1484	1097	884	752	654	585	532	490	454

Temperature: 25°C
12.02.2004

BAE Batteries USA

ENERGY FROM BATTERIES

The current system uses BAE Secura 25-OGi-2000 single-cell, vented, or flooded lead-acid batteries (LAB). Each 1100kVA RUPS unit connects to 264 battery cells installed on metallic racks. These battery cells are connected in series to provide voltage corresponding to the nominal UPS input battery voltage of 520V (585V max) required for system operation. The potential difference between battery cell terminals is at a universal voltage of 2 volts per cell (VPC), and the float is at the voltage of 2.23VPC. The total LA-BESS voltage is, therefore, equal to 528V (2VPC x 264 cells). The battery system voltage at float is 588.72V (2.23VPC x 264 cells). These batteries can provide 1100kVA of clean and conditioned power during power disturbances or forced power outages [2,3,17,22]. The design of the current RUPS system was to provide a 15 minutes backup time at full UPS loading with battery cells' end, or final voltage (*Uf*) set to reach 1.8VPC. From Equation 2.1 and based on the maximum installed capacity, the determination of the battery power is as per Equation 2.2 below:

$$P_{bat\text{-}RUPS} = \frac{S \times \cos\varphi}{\eta_{RUPS}} = \frac{1100 \times 0.8}{0.92} = 956.52kW \tag{2.2}$$

The battery discharge direct current is read directly from the RUPS' nameplate and found to be equal to 1819A. This current can also be calculated as the ratio between the full rated RUPS power to the system voltage and is 1100/600 = 1833A. Referring to BAE project planning data shown in Table 2.1, for a constant discharge current of 1886A as indicated, which is higher than the system discharge-current read from the nameplate or calculated, the LA-BESS UPS is able to sustain the full load power for a run-time of up to 15 minutes [2,3]. Correspondingly, referring to BAE project planning data shown in Table 2.2, the constant discharge power per cell as indicated is found to be equal to 3456W. These determinations lead to having the designed storage or amp-hours capacity for the LA-BESS be equal to 2000Ah, and the designed power be equal to 912.4kW (3.456kW/cell x 264 cells), and the cut-off voltage be equal to 475.2V (1.8VPC x 264 cells) [2].

2.1.3. Cell heat-dissipation

The RUPS system uses BAE OGi single-cell, vented, or flooded lead-acid batteries. Each RUPS has 264 BAE Secura 25-OGi-2000 cells connected in series. A considerable amount of heat transforms over and above the alteration of mass and exchange or transfer of electrical energy emanating from the chemical reactions during the float, discharge, and charge operation [1,2,3,17,20].

Float operation: The heat dissipation power during the float operation mode for one cell can be calculated by Equations 2.3 & 4 below:

$$P_{float} = \left(U_{float} - U_{gas}\right) \times I_{float} + R_i \times I_{ac}^2 \quad (2.3)$$

Where, U_{float} is the float voltage given to be equal to 2.23VPC, U_{gas} is the constant describing the water decomposing voltage given to be equal to 1.48V for all flooded batteries assuming that all the current is used for water decomposition, I_{float} is the float current (at normal conditions of 20℃ operating temperature and 2.23VPC float voltage, the float current is nearly 25mA/100Ah of nominal capacity for flooded or vented batteries and during battery lifetime this float current increases by a factor of 1.5 to 2 caused by antimony poisoning of the batteries), Ri is the internal resistance of the cell equal to 0.09mΩ (the internal resistance depends on the plate design of the cells and the capacity as read from BAE 25-OGi-2000, vented lead-acid cells batteries - technical specification), and I_{ac} is the effective ripple current of the charging unit (according to EN 50272-2, the maximum allowed permanent ripple current is 5A/100Ah).

$$P_{Float} = (2.23 - 1.48) \times \left[2000Ah \times \frac{25mA}{100Ah}\right] + 0.09 \times 10^{-3}\Omega \times \left[\left(\frac{5A}{100Ah}\right) \times 2000Ah\right]^2 = 1.275W \quad (2.4)$$

Discharge operation: Heat dissipation during discharge operation depends on the discharge current and the difference between open-circuit voltage (U_0 = 0.84 + electrolyte gravity) and the actual discharge voltage of the battery cell. The use of Equations 2.5 & 6 below will calculate heat dissipation per cell:

$$P_{discharge} = \left(U_0 - U_{discharge}\right) \times I_{discharge} \quad (2.5)$$

For all calculations, a discharge during 1 hour is assumed with a final voltage of 1.8VPC. As for the discharge current, we will select the corresponding 1-hour discharge current (I_{1h}) from the BAE project planning data.

$$P_{discharge} = [(0.84+1.24)-1.8] \times 1069 = 299.32W \quad (2.6)$$

Recharge operation: The calculation is nearly the same as at discharge operation. The heat dissipation is now a product of the mean value of recharge current and the difference between the open circuit. The recharge voltage as in Equations 2.7 & 8. We will neglect the heat dissipation due to the ripple current because it is less than 5% of the recharge-current effect. The calculation is carried out for an initial recharge current of 1.5 x I_{10} (nominal current) and a boost charge voltage of 2.4V. The recharge time for the calculation is limited to a charging factor of 1. The average current during the boost charge operation can be assumed to be 90% of the initial charging current.

$$P_{recharge} = \left(U_{recharge} - U_0\right) \times I_{recharge} \quad (2.7)$$

Recharge during 360 minutes (6 hours) of BAE 25-OGi-2000 cell, initial charging current 200A, the average charging current will then be = 1.5 x I_{10} x 0.9 = 1.5 x 200 x 0.9 = 270A.

$$P_{recharge} = [(2.23 \pm 1\%)-(0.84+1.24)] \times 270 = 46.52W \quad (2.8)$$

2.1.4. Battery Room Ventilation

The battery room consists of the heating, ventilation, and air conditioning (HVAC) #1 & 2 which are of York make and require a 3-phase supply. The rated cooling and heating input powers of HVAC#1 are, respectively, 21kW and 14kW, and for HVAC#2, these powers are, respectively, 16kW and 14kW.

2.1.5. LA-BESS Footprint and Floor Loading Capacity

The 264 batteries associated with each RUPS are double stacked into four rows (lower and upper row), each row containing 66 cells:

Cell length x width x height = 0.44 x 0.21 x 0.67m

Cell surface area = 0.44 x 0.21 = 0.0924m²

The total area occupied (excluding ventilation gaps) = 0.0924 x 132 = 12.2m²

The total area occupied (including ventilation gaps) = 16.4 x 1.75 = 28.7m²

The total area occupied by batteries of all UPSs = 28.7 x 4 = 114.8m²

Cell weight = 154.085kg

The total cells weight (excluding racks weight) = 154.085 x 264 = 40678.44kg

The total weight for all 4 batteries banks = 154.085 x 1056 = 162713.76kg

2.1.6. RUPS System Findings and Drawbacks

The four Piller RUPSs installed are over 26 years old, spare parts are no longer available, the equipment and die to produce a replacement unit are no longer available. Although they are still operational, any significant failures would most likely also make them unrepairable. With ageing, they now require regular heavy maintenance and suffer higher electromechanical energy losses inherent to pony motor, frictional, windage. When compared to new UPSs, they are running at high operation loss due to their low power factor (0.8), low efficiency (92%), high heat dissipation, and a requirement for high room ventilation. They are bulky and occupy high footprint space. Like with most equipment, current specifications differ totally from or bear little resemblance to those of earlier years, experiences and technical developments have shown the previous specifications to be deficient. Examples of differing requirements between earlier and current standards relate to operating mechanisms, diagnostic coverage, and personnel protection during equipment failure. On the other end, the associated BAE 25-OGi-2000 LA-BESS now requires biannual maintenance costing the organization approximately R300 000 annually. Although this is considered a legitimate running cost of the plant, it occurs on a capital scale with repetitions of 8 to 10 years. The cost of a cell in 2021 is seating at around R35 000. All cells came with an initial 2-year warranty. The extension of this warranty by an additional three years cost the facility approximately R700 000. Even though the BAE battery cell has a prescribed life expectancy of 20 years, various aspects can undesirably influence it. During normal operation of flooded cells, a considerable amount of heat dissipated adds to the system running cost. Due to the presence of hydrogen, the battery room requires high ventilation to monitor its concentration. The battery room is zoned (zone 1) hazardous utilizing costly explosion-protected electrical and hydrogen monitoring equipment.

2.2. Conceptualization of the New System

There are multiple UPS configurations available nowadays. The main configuration types are line-interactive type, online double-conversion type, and offline type. Decisions of what configuration type to be selected are mainly market, requirements, and choices related more than their technological expertise. Identification and selection of a well-suited UPS for any application are concluded by thoroughly type-examining its designed features and benefits towards the facility to be protected. Before selecting a suitable UPS system, it is vital to define its functional and parameters-based performance structures to which its design this UPS is developed. It is also equally crucial to determine requirements such as power, safety, availability, maintainability, affordability, scalability, design performance, configuration type, full autonomy, and capability to condition all NRS-048 defined imperfections. These requirements will assist the system in achieving its optimum integrity and performance level. From that, a parallel UPS system comprising of four Eaton Power Xpert 9395P High-performance, Four-UPM, 600/600VAC, 1100kVA modular SUPSs configured as per Figure 2.2 has been specified; their main specifications are as in Table 2.4. They offer improved lower-load-rate efficiency, performance, power protection capability, reliability, and reduced overall operating costs. Other additional benefits offered by the Eaton Power Xpert 9395P High-performance SUPS include the lowered total cost of ownership (TCO), the employment of a three-level converter topology, the field-installed uninterruptible power module (FI-UPM) capability, the modularity design, the employment of variable module management system (VMMS) and energy saver system (ESS), the easy capacity test (ECT) capability, and the deployment of advanced battery management (ABM) technology [10,11].

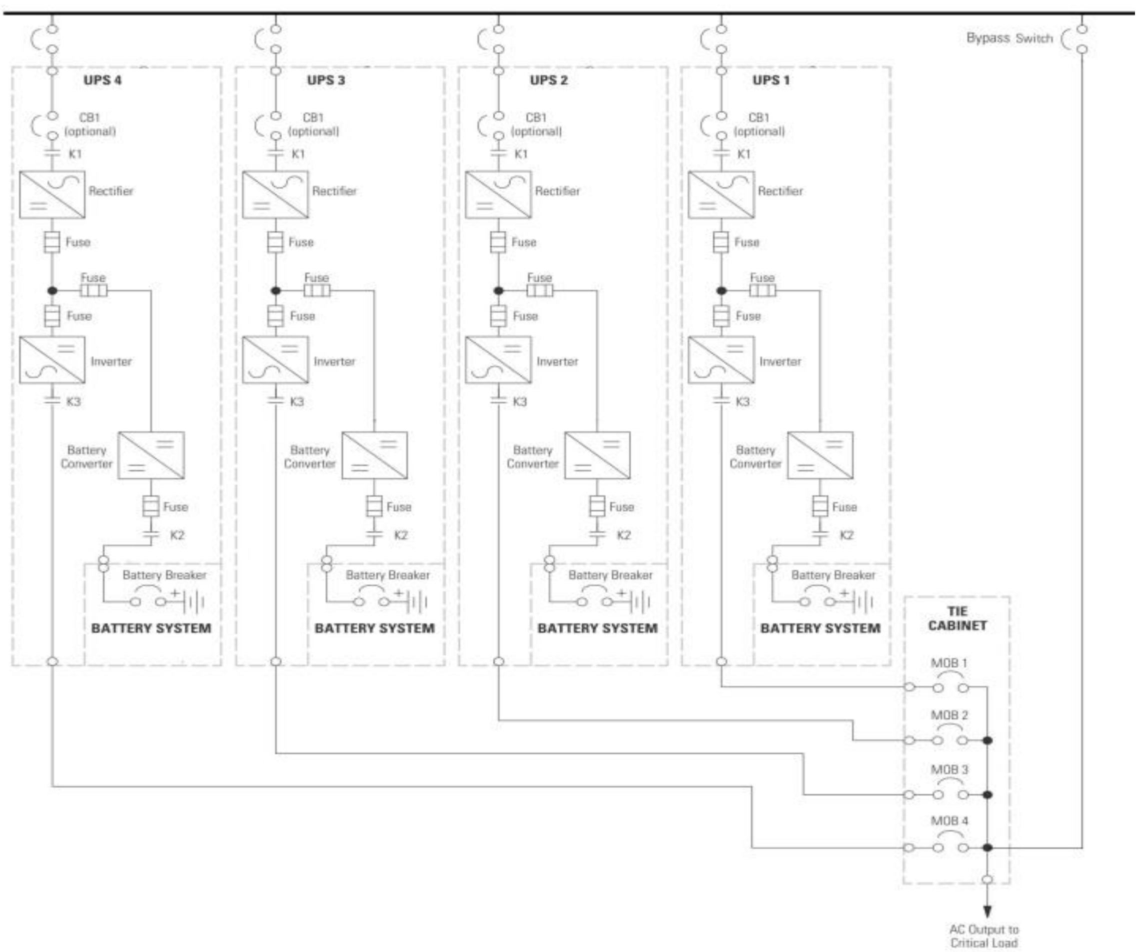


Figure 2.2. Parallel system with centralized maintenance bypass

Table 2.3. Samsung 128S1P Technical Data [8]

CONSTANT POWER DISCHARGE RATINGS - kW PER STRING @ 25℃

MUNUTES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
INITIAL CAPACITY	213.0	210.0	207.0	204.0	201.0	195.0	190.0	184.0	172.9	154.5	140.7	129.2	119.4	110.2	103.0	96.8	91.2	86.2	81.7	77.6
FINAL CAPACITY	210.0	201.0	195.0	190.0	177.0	162.0	155.0	147.0	135.0	122.9	111.7	102.4	94.6	87.8	81.9	76.8	72.3	68.3	64.7	61.5
MUNUTES	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
INITIAL CAPACITY	74.5	71.4	68.4	65.3	62.2	60.1	58.0	55.9	53.8	51.7	50.5	49.4	48.2	47.1	45.9	44.8	43.6	42.5	41.3	40.2
FINAL CAPACITY	59.0	56.6	54.1	51.7	49.2	48.1	46.4	44.8	43.1	41.0	40.1	39.2	38.3	37.3	36.4	35.5	34.6	33.7	32.8	31.9
MUNUTES	**41**	**42**	**43**	**44**	**45**	**60**	**90**	**120**	**180**	**240**	**300**	**360**	**420**	**480**						
INITIAL CAPACITY	39.0	37.9	36.7	35.6	34.4	25.8	17.2	13.0	8.6	6.5	5.2	4.3	3.7	3.2						
FINAL CAPACITY	31.0	30.0	29.1	28.2	27.3	20.5	13.7	10.2	6.8	5.1	4.1	3.4	2.9	2.6						

ITEM	SPECIFICATION	REMARKS
NUMBER OF CELLS PER CABINET	128	8 CELLS PER MODULE
NOMINAL CAPACITY PER CABINET	32.6kWh	1/3C @ R.T.
NOMINAL VOLTAGE	486.4VDC	3.8V/CELL
MAXIMUM VOLTAGE	537.6VDC	4.2V/CELL
END OF DISCHARGE VOLTAGE	384VDC	3.0V/CELL
MAXIMUM DISCHARGE CURRENT	600A	1-SECOND PULSE
SHORT CIRCUIT CURRENT	7400A	
FLOAT CHARGE VOLTAGE	537.6VDC	4.2V/CELL
RECOMMENDED CHARGE CURRENT	22.3A	PER CABINET
MAXIMUM CHARGE CURRENT	250A	2-SECOND PULSE
RECOMMENDED OPERATING TEMPERATURE	23℃ +/- 5℃	AMBIENT
STORAGE TEMPERATURE	0 - 40℃	
STORAGE HUMIDITY	LESS THAN 60% RH	NON-CONDENSING
ELECTROLYTE WEIGHT PER CELL	343g	128 CELLS PER CABINET

OVERCURRENT PROTECTION TRIGGER CURRENT

600A	1 SECOND
540A	10 SECONDS
495A	30 SECONDS
470A	60 SECONDS

2.2.1. SUPS Footprint and Floor Loading Capacity

SUPS length x width x height = 5.659 x 0.873 x 1.88m
SUPS surface area = 5.659 x 0.83 = 4.94m²
The total area occupied by all SUPSs = 4.94 x 4 = 19.76m²
SUPS weight = 5239kg
The total weight of all SUPSs = 5239 x 4 = 20956kg

2.2.2. Lithium-ion BESS (LI-BESS) Rating

The system uses prismatic LMO lithium-ion battery (LIB) cells - Samsung SDI and 128S1P cabinets. Each cabinet will contain 16 battery modules for every single string, and these battery modules will be series-connected via provided busbar links [7,8,9,10,15,23,24]. The module configuration is 8S1P (8 x 1S1P cells per module), the cell voltage is equal to 3.8 V, and the nominal cell capacity and discharge energy are, respectively, 67Ah and 254Wh (67Ah x 3.8VPC). Given these cell parameters, the module voltage will, therefore, be equal to 30.4V (8 x 3.8VPC); the nominal module capacity and discharge energy are, respectively, 67Ah and 2.036kWh (8 x 254Wh/cell or 67Ah x 30.4V); and the cabinet voltage is equal to 486.4V (16 x 30.4V/module). The nominal cabinet capacity and discharge energy are, respectively, found to be 67Ah and 32.6kWh (16 x 2.036kWh/module or 67Ah x 486.4V). Similarly, from using Equation 2.1 and based on the maximum installed capacity of 1100kVA per SUPS, the battery power is determined as per Equation 2.9 below:

$$P_{bat\text{-}SUPS} = \frac{S \times \cos\varphi}{\eta_{SUPS}} = \frac{1100 \times 1}{0.97} = 1134.02\ kW \qquad (2.9)$$

Based on the technical data in Table 2.3 and Equation 2.9, for a backup time not exceeding 20 minutes, we can deduce that the number of parallel battery racks or cabinets associated with each SUPS unit is equal to 1134/61.5 = 18.44, rounded up to 20. The total designed storage or amp-hours capacity for LI-BESS is, therefore, 67Ah x 20 = 1340Ah, and the total designed constant discharge power rating is 61.5kW/rack x 20 racks = 1230kW.

2.2.3. LI-BESS Footprint and Floor Loading Capacity

The 20 battery cabinets associated with each SUPS will stack into two rows. Each row containing ten cabinets installed side-by-side and rear-to-rear in a so-called '128S20P' configuration:

Cabinet model: 128S1P
Cabinet length x width x height = 0.65 x 0.53 x 2.281m
Cabinet surface area = 0.65 x 0.53 = 0.3445m²
The total area of two rows of cabinets associated with one SUPS = 0.3445 x 20 = 6.89m²
The total area of all eight rows of cabinets associated with SUPSs = 6.89 x 4 = 27.56m²
Cabinet weight = 482kg
The total weight of each system = 482 x 20 = 9640kg
The total weight of all four systems = 9640 x 4 = 38560kg

2.3. Comparative Analysis

The four old 3-phase LAB-RUPSs and the four newly selected modular double-conversion LIB-SUPSs of the same size will comparatively be analysed. The main characteristics of both UPS systems to be analysed are specified in Table 2.4 [11,16,22].

Table 2.4. UPS Main Characteristics

UPS Details	Rotary UPS	Static UPS
UPS Type	Piller UB1100S	Eaton Xpert 9395P
BESS	Lead-acid	Lithium-ion
UPS modules	4	4
Input/output voltage	600/600VAC	600/600VAC
UPS module rating	1100kVA	1100kVA
UPS efficiency	92%	97%
Input power factor	0.8	1
Total output power	1100 x 0.8 = 880kW	1100 x 1 = 1100kW

2.3.1. Assumptions

All calculations will base on the following assumptions. Based on data obtained from Eskom, the facility had 67 interruptions sustained above 5 minutes in the past ten years [13], giving an average of 7 interruptions per year. For that, we assume to have seven complete battery discharges and recharges a year. The discharge is made through a full 15min design backup time to translate to a monthly discharge period of 0.146 hours (7 x 15 minutes/12 x 60). Each charging process takes 6 hours and translates to a monthly charge period of 3.5 hours (7 x 6 hours/12 = 3.5 hours). With the average number of hours per month taken to be 730 hours and based on monthly discharge and charge periods determined above, we can deduce that LAB will be in floating operation for the rest of the time when not discharging or charging; this is equivalent to 726.35 hours a month. Two ventilation units control battery room temperature and prevent the unsafe accumulation of hydrogen gas. The system design allows the run of both ventilation units for LAB and only one single ventilation unit for LIB at fully rated capacity during summertime (low-demand season) to compensate for their winter (high-demand season) consumptions. Through energy transformation from electrical to heat developed in our system, we will assume that of every Watt of dissipated heat energy by any equipment, 60% Watt of electrical power is being consumed.

The facility uses the 'Miniflex' electricity tariff structure from the power utility. This tariff structure is one of the time-of-use (TOU) electricity tariffs for urban customers with a notified maximum demand (NMD) from 25kVA up to 5MVA. TOU tariff means a tariff with energy charges that change during different TOU periods and seasons. This TOU tariff is commonly used in developed economy countries as it is structured to incentivise consumers who lower their consumption during peak periods. The TOU periods typically are peak, standard, and off-peak periods and differ during high and low demand seasons.

As more critical loads add to the UPS system, a high amount of power will need to be processed by various main components (inverter, rectifier). The losses emanating from these components will vary in proportion to critical loads, so are the energy charges during TOU periods and seasons. With this TOU electricity tariff structure having an economic impact on the wasted energy costs from both UPS systems, the accurate energy losses costs in alignment with the facility consumption profile or behaviour will need to be determined. Unfortunately, the main concern from previous researches while evaluating UPS system losses was to consider a fixed average energy charge in their annual energy losses calculations. UPS system annual energy losses costs specification based on an average energy charge will unfortunately not be load-profiled to the facility's energy consumption profile nor adapted to the power utility's charges through various seasons and time of the day. To specify these energy losses costs more accurately, the wasted energies distribution must follow the realistic energy profile or consumer behaviour and get charged per their time-of-use.

The determination of total cost of ownership will base on energy costs from Eskom's time of use, 2020/2021 Miniflex tariff structure where all ancillary charges are included [12]. Energy distribution through this comparison is made in alignment with facility 2019/2020 consumption behaviour, and deduced energy distribution coefficients are as below:

High-demand season (HDS) energy distribution ratios:

Peak energy average = 0.309X
Standard energy average = 0.794X
Off-peak energy average = X
(X + 0.309X + 0.794X) = Y
X = Y ÷ 2.103
Y = Total seasonal energy calculated
X = Multiplying factor = Off-peak energy

Low-demand season (LDS) energy distribution ratios:

Peak energy average = 0.297X
Standard energy average = 0.759X
Off-peak energy average = X
(X + 0.297X + 0.759X) = Y
X = Y ÷ 2.056
Y = Total seasonal energy calculated
X = Multiplying factor = Off-peak energy

2.3.2. RUPS Losses Calculation and Energy Distribution

All energy distributions calculated below are inserted in 2020/21 Eskom's tariff input sheet; respective costs are as in Table 2.8.

a) RUPS heat energy loss: With the maximum heat dissipation of each RUPS given to be 87kW, 60% of this heat represents electrical power consumed and is equal to 87 x 0.6 = 52.2kW. For all four RUPSs running throughout 730 hours of the month, the monthly electrical energy is equal to 52.2 x 730 x 4 = 152424kWh.
b) Battery room cooling loss: For the LAB room, the assumption is to run both ventilation units at their fully rated capacity during summertime. Total cooling power of both air conditioning units used is (21 + 16) = 37kW leading to a monthly electrical energy of 37 x 730 = 27010kWh.
c) Rated operation loss: As calculated, the rated loss is equal to 76.5kW, and for all four UPSs running throughout 730 hours of the month, the monthly electrical energy is equal to 76.5 x 730 x 4 = 223380kWh.
d) Batteries floating operation loss: As calculated in Section 2.1.3, the heat load during floating operation per cell was 1.275W, 60% of this heat represents electrical power consumed, and for all 1056 cells floating 726.35 hours a month as demonstrated in Section 2.3.1, the monthly electrical energy will then be equal to 1.275 x 0.6 x 1056 x 726.35 = 587kWh.

e) Batteries discharge operation losses: As calculated in Section 2.1.3, the heat load during discharge operation per cell was 299.32W, 60% of this heat represents electrical power consumed, and for all 1056 cells discharging 0.146 hours on average a month as demonstrated in Section 2.3.1, the monthly electrical energy will then be equal to 299.32 x 0.6 x 1056 x 0.146 = 27.7kWh.

f) Batteries recharge operation losses: As calculated in Section 2.1.3, the heat load during recharge operation per cell was 46.521W, 60% of this heat represents electrical power consumed, and for all 1056 cells charging 3.5 hours on average a month as demonstrated in Section 2.3.1, the monthly electrical energy will then be equal to 46.521 x 0.6 x 1056 x 3.5 = 103.165kWh.

g) HDS - Energy wasted

Y = 152.42 + 223.38 + 0.587 + 0.028 + 0.103 = 376.518MWh
X = Off-peak energy = 376.518 ÷ 2.103 = 179.04MWh
Peak energy = 179.04 x 0.309 = 55.32MWh
Standard energy = 179.04 x 0.794 = 142.16MWh

h) LDS - Energy wasted

Y = 152.42 + 27.01 + 223.38 + 0.587 + 0.028 + 0.103 = 403.528MWh
X = Off-peak energy = 403.528 ÷ 2.056 = 196.27MWh
Peak energy = 196.27 x 0.297 = 58.29MWh
Standard energy = 196.27 x 0.759 = 148.97MWh

i) HDS - Backup energy

Y = 4400 x 0.8 x 0.146 = 514kWh
X = Off-peak energy = 514 ÷ 2.103 = 244.41kWh
Peak energy = 244.41 x 0.309 = 75.52kWh
Standard energy = 244.41 x 0.794 = 194.1kWh

j) LDS - Backup energy

Y = 4400 x 0.8 x 0.146 = 514kWh
X = Off-peak energy = 514 ÷ 2.056 = 250kWh
Peak energy = 250 x 0.297 = 74.25kWh
Standard energy = 250 x 0.759 = 189.75kWh

2.3.3. SUPS Losses Calculation and Energy Distribution

Like in Section 2.3.2, all energy distributions calculated below are inserted in 2020/21 Eskom's tariff input sheet; respective costs results are as in Table 2.8.

a) SUPS heat energy loss: With the maximum heat dissipation of each SUPS given to be 61kW, 60% of this heat represents electrical power consumed and equal to 61 x 0.6 = 36.6kW. For all four UPSs running throughout 730 hours of the month, the monthly electrical energy is equal to 36.6 x 730 x 4 = 106 872kWh.

b) Heat output from battery cabinets: With the maximum heat dissipation of each battery cabinet given to be 567BTU/hour, and with 1BTU/hour equal to 0.2931W, the heat dissipation in Watt will then be 567 x 0.2931 = 166.131W = 0.166kW. With 60% of this heat representing electrical power consumed, the active electrical power consumed will be equal to 0.166 x 0.6 = 0.0996kW. For all 80 (20 x 4) cabinets running throughout 730 hours of the month, the monthly electrical energy is equal to 0.0996 x 730 x 20 = 5816.64kWh.

c) Battery room cooling loss: For the LIB room, the assumption is to run only one ventilation unit at its fully rated capacity during summertime. Use one single air-conditioning unit of 16kW rated capacity. This assumption leads to a monthly electrical cooling energy of 16 x 730 = 11680kWh.

d) SUPS rated operation loss: As calculated, the rated loss is equal to 34.02kW, and for all four UPSs running throughout 730 hours of the month, the monthly electrical energy is equal to 34.02 x 730 x 4 = 99338.4kWh.

e) Batteries waste heat energy during floating, discharge, and recharge operation is zero since the cycle operation of battery cells is controlled by a battery management system (BMS).

f) HDS - Energy wasted

Y = 106.87 + 5.817 + 99.34 = 212.027MWh
X = Off-peak energy = 212.027 ÷ 2.103 = 100.82MWh
Peak energy = 100.82 x 0.309 = 31.15MWh
Standard energy = 100.82 x 0.794 = 80.05MWh

g) LDS - Energy wasted

Y = 106.87 + 5.817 + 11.68 + 99.34 = 223.707MWh
X = Off-peak energy = 223.707 ÷ 2.056 = 108.807MWh
Peak energy = 108.807 x 0.297 = 32.316MWh
Standard energy = 108.807 x 0.759 = 82.58MWh

h) HDS - Backup energy

Y = 4400 x 1 x 0.146 = 642.4kWh
X = Off-peak energy = 642.4 ÷ 2.103 = 305.47kWh
Peak energy = 305.47 x 0.309 = 94.4kWh
Standard energy = 305.47 x 0.794 = 242.54kWh

i) LDS - Backup energy

Y = 4400 x 1 x 0.146 = 642.4kWh
X = Off-peak energy = 642.4 ÷ 2.056 = 312.45kWh
Peak energy = 312.45 x 0.297 = 92.8kWh
Standard energy = 312.45 x 0.759 = 237.15kWh

2.3.4. Results

The summary of the footprint and weight analysis between SUPS and RUPS systems and the respective BESS they employ are as in Table 2.5 & 6. The storage capacities and usable energy densities comparisons between SUPS and RUPS systems are as in Table 2.7. The net variance in the total annual running costs between SUPS and RUPS systems is as in Table 2.8 below [5]. It is worth mentioning that, in most of the previously cited researches, the comparison of the energy density between LAB and LIB refers to the weight of the battery system (W/kg) like in the case of [21,25]. In contrast, this paper will express this energy density differently based on the cell amp-hour or energy storage capacity (W/Ah). The expression will represent the actual depth of energy collection by each battery technology; the result will best highlight the development that the LIB chemistry has introduced in the usable energy density boosting compared to the LAB chemistry.

Table 2.5. Footprint Comparisons

UPS Details	UPS Footprint (m^2)	BESS Footprint (m^2)	Total Footprint (m^2)
LAB-RUPS	27.245	114.8	142.045
LIB-SUPS	19.76	27.56	47.32

Table 2.6. Weight Comparisons

UPS Details	UPS weight (kg)	BESS weight (kg)	Total weight (kg)
LAB-RUPS	47 560	162 713.76	210 273.76
LIB-SUPS	20 956	38 560	59 516

Table 2.7. Storage Capacities and Energy Densities

Details	LA-BESS	LI-BESS
Usable Power	880kW	1100kW
Designed Power	912.4kW	1230kW
Designed Amp-hour Capacity	2000Ah	1340Ah
	2000/1340 = 1.4925	
	LAB designed Amp-hour capacity = (1.4925 - 1) x 100 = 49.25% of LIB	
Designed Energy Density	912.4/2 000 = 0.456kW/Ah	1230/1340 = 0.918kW/Ah
	0.456/0.918 = 0.497	
	LAB designed density = (0.497 - 1) x 100 = - 50.3% of LIB	
Usable Energy Density	880/2000 = 0.44kW/Ah	1100/1340 = 0.821kW/Ah
	0.44/0.821 = 0.536	
	LAB designed density = (0.536 - 1) x 100 = - 46.4% of LIB	

Table 2.8. Costing Summary Analysis

Energy details and charges	RUPS	SUPS
Total system energy losses per year	R 7 799 263	R 5 285 168
Off-grid backup savings	R 2 128 406	R 2 130 257
Actual annual RUPS losses cost (operation losses – Off-grid savings)	R 5 670 857	
Actual annual SUPS losses cost (operation losses – Off-grid savings)	R 3 154 911	
Annual TCO savings	R 2 515 946	
4 x SUPS purchasing price	R 8 977 528	
4 x LI-BESS purchasing price	R 28 791 920	
Return on investment (UPSs only)	3.57 Years	
Return on investment (UPS+BESSs)	15.01 Years	

a) RUPS power density: Referring to the main characteristics of both UPS systems in Table 2.4, the total active output power that each RUPS can deliver is 880kW. With the space footprint that takes up the system's weight found to be $142.045m^2$, the power density will be equal to 880 ÷ 142.045 = $6.2kW/m^2$.
b) SUPS power density: Referring to the main characteristics of both UPS systems in Table 2.4, the total active output power that each SUPS can deliver is 1100kW. With the space footprint that takes up the system's weight equal to 46.36 m^2, the power density will be 1100 ÷ 47.32 = $23.24kW/m^2$.
c) From the results above, the percentage power density of the LAB-RUPS system is [(6.2 ÷ 23.73) – 1] x 100 = 73.873% less than that of the LIB-SUPS system.
d) From the results in Table 2.5, the percentage spatial footprint of the LAB-RUPS system is [(47.32 ÷ 142.045) – 1] x 100 = 66.7% less than that of the LIB-SUPS system.
e) From the results in Table 2.6, the percentage floor loading capacity of the LAB-RUPS system is [(59 516 ÷ 210 274) – 1] x 100 = 71.7% less than that of the LIB-SUPS system.
f) With the yearly facility energy cost seating at R28 millions for the annual energy consumption of 21753MWh based on losses calculation in Section 2.3.2, the RUPS energy loss contribution is 27.5% and 21.22% of the total annual cost and energy consumed, respectively. Similarly, based on losses calculation in Section 2.3.3, the SUPS energy loss contribution is 18.4% and 11.54% of the total annual cost and energy consumed, respectively. The annual TCO savings represents 9.2% of the total yearly energy cost of the facility.
g) From losses calculation in Section 2.3.2 and 2.3.3, the new LIB-UPS offers up to 56% (2649.4MWh ÷ 4761.3MWh = 0.5565 x 100 = 55.65%) less heat dissipated when compared to the existing LAB-RUPS system on an annual basis.

3. Conclusions

The new SUPS system has a prominent fiscal return that offers a lesser total cost of ownership with up to 56% less heat dissipated when compared to the existing RUPS system. This fiscal return is so great that the upgrade allows the facility to pay back the invested capital into SUPS units and SUPS+BESSs in approximately 4 and 15 years, respectively. We can also conclude that, to reduce the total cost of ownership of any UPS technology, it is imperative, amongst other requirements, to lower cooling and system operating energies. This lowering of energy leads to reducing consequential exposure to ever-escalating energy tariff, carbon footprint, and increase competitiveness in energy management and savings. The LIB-SUPS system has a substantial and prominent reduction in weight and spatial footprint reduction and has higher power density than the existing RUPS system. The miniaturization and compactness of components used in LIB-SUPS benefited from various upgrades, high-frequency and high-power semiconductors usage has drastically and significantly contributed to this overall footprint and weight reduction when compared with a traditional LAB-RUPS system. And, while the development of LIB cell chemistries has gained pace to enhance and optimize their performances vis-à-vis of the LAB technology, improvement in cell weight and space footprint they occupy is also not surrendered. Based on the design requirements to support the full load power for 15 to 20 minutes of autonomy, we can conclude that the usable energy density of the LA-BESS is 46.4% less than that of the LI-BESS, the storage capacity of the LA-BESS is 49.25% more than that of the LI-BESS. The development of LIB chemistry has introduced greater energy density boosting. This energy density boost caused the quantity of service power collected at the given state of its maximum stored energy charge to nearly double compared to the amount of energy charge sourced from the LAB technology maximum stored energy charge. This statement comes from the fact that LIBs have a depth of discharge of up to 100% (DoD ≤ 100%) compared to only up to 80% (DoD ≤ 80%) for BAE LABs. This deep energy collection is conducted safely by innovative battery management systems implanted at the module, cabinet, and BESS level to offer condition-based monitoring and management of cells' functionality and health.

Although this explorative study design draws some similarity from previous researches, as demonstrated above, it provides repudiation to past approaches on how the costs of UPS system losses are determined. The current work, serving as an introduction of this exciting approach to the technical audience, highlights how various factors of the studied UPS systems play out in a specific application where the facility-based energy profile behaviour can assist in determining their losses costs more concretely. Given the narrow focus on a single specific facility, one can get a contextualized understanding of how the UPS system can be analyzed, evaluated, and selected based on a fully informed decision-making and related application.

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