WHITE PAPER

SKELGRID: ENERGY STORAGE SYSTEM FOR THE GRID

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Electric energy storage is becoming an important part of power grids, allowing to better integrate renewables, implement frequency regulation, improve transmission and distribution (T&D) systems' performance, grids' reliability, and power quality for manufacturers ranging from electronics and semiconductor factories to bottling plants.

Energy storage systems are packaged solutions for these advanced grid applications. Skeleton Technologies has launched SkelGrid – a modular energy storage system well-suited for the grid. Modularity offers many advantages – the flexibility towards capacity, power, and application time requirements, more optimizable solutions and less risk associated with large transmission and distribution grid investments compared to non-modular energy storage solutions.

SkelGrid is based on Skeleton's SkelCap ultracapacitors, which offer a lower initial cost and lower total cost of ownership alternative to traditional battery-based solutions in numerous applications. Frequency regulation, backup power and power quality control only a few of them.

Ultracapacitors offer up to 1M deep charge-discharge cycles and very high power and efficiency, making them much more cost-effective if relatively short (up to 60 seconds) power surges are necessary. Even the high-power batteries are always oversized for relatively short power surges and require frequent replacing due to the short lifetime under such conditions.

For example, starting (multiple) high capacity generators at the same time requires a very high power surge, which would require oversized battery banks and affect their lifetime significantly. For mobile applications, batteries are often just too bulky, especially if high power levels are required. Furthermore, due to low efficiency batteries require high initial investment in cooling systems. In applications where constant or occasional power peaks are short and significantly higher than base power demand, ultracapacitors can help to downsize a generator's capacity for it to work at maximum efficiency, and therefore, save fuel.

1. Applications for SkelGrid

1.1. High power for short duration

Ultracapacitors are an ideal technology for fast and high power applications. Covering high power peaks with batteries requires an oversized battery bank (Figure 1), and results in a higher price per kWh (Figure 2). The price per battery installation gets especially high at short application times of less than 10 seconds, as less than 2% of total battery

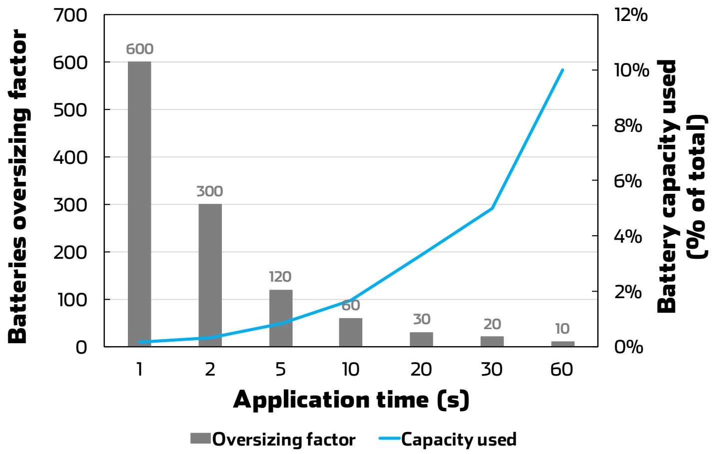

Fig. 1 Battery bank oversizing factor dependence on application time and the percentage of total capacity used.of an ultracapacitor

capacity is used when discharged at the 6C rate. For an application time of 1 second, the battery bank has to be oversized about 600 times, making the cost significant if power at megawatt levels is necessary.

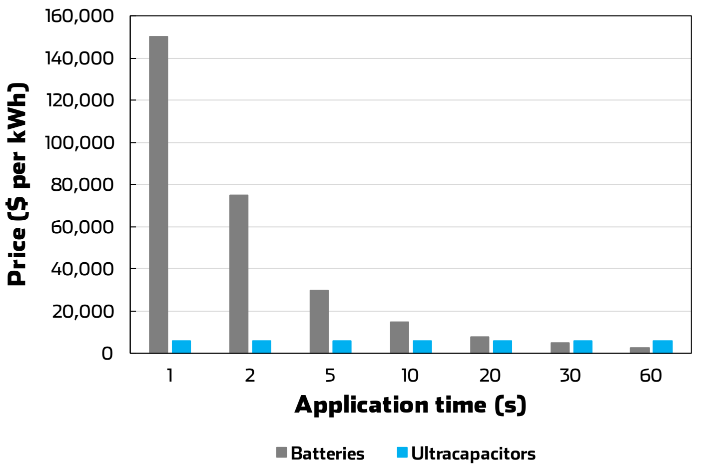

Fig. 2 Price per kWh for the installation in case of batteries and ultracapacitors at various application times.

1.2. Peak power supply

Almost all power profiles in the grid or in industrial manufacturing are dynamic - in addition to baseline power a certain period of peak power is required - this is where ultracapacitors come in handy. Ultracapacitors fill the gap between base and peak load, as the generators sized for covering peak load will be very inefficient at low base load levels.

For example, if the peak load is ~900 kW and the base load ~300 kW, the difference in fuel consumption may be more than twice higher per kWh, due to reduced efficiency when operating at low capacity. Running a genset at a low load also causes damage to the generator. Implementing ultracapacitors allow to downsize the genset to base load level and operate the genset at its maximum efficiency, and therefore, save fuel. Ultracapacitors are economical in handling relatively short peaks, offering maintenance-free technology and a cheaper solution when compared to batteries, as the battery banks have to be dramatically oversized for covering high power for a short duration (Figure 1).

1.3. Bridging power

In the case of a failure in a microgrid, starting another generator is not instantaneous. To provide reliable power at all times, a backup power solution to cover the cap between switching from one genset to another is needed. Batteries must be oversized for the application, as the application time is measured in seconds, resulting in a notably high price for the installation. Holding a backup genset idling wastes fuel and results in additional costs. Ultracapacitors have extremely fast response rate and can provide high power at much lower cost, suited for short duration bridging power applications.

1 The price of batteries is estimated to roughly $250/kWh in case of deep discharge, and $5700/kWh for ultracapacitors (calculated from usable energy). The calculations are presented for illustrating purposes - to stress the need of oversizing battery banks for fast, high power applications.

1.4. Backup power and power quality

Ultracapacitor systems can provide a solution for power quality and power outage issues for industry, hospitals, data centers, and other critical infrastructure. For example, in the semiconductor industry, "voltage sags" or "voltage dips" are the most common power quality problem and cause downtime, scrap, and economic losses.

A voltage sag is defined as a voltage drop below 90% of the nominal voltage, which may be caused by abrupt increases in load such as short-circuits or faults, motors starting, or electric heaters turning on, but also by increases in source impedance, typically caused by a loose connection. Voltage sags can arrive from utility as well as be generated inside a building. A power outage lasting for under a second can damage all the products on the production line, and the losses are compounded by the unavoidable downtime of clearing the production line and setting everything up again. Voltage sags can be covered using backup power technology such as batteries or ultracapacitors. However, as the industry SEMI™ F47 standard requires equipment to cover voltage sags of up to 2 seconds to prevent production losses, ultracapacitors offer significant economic benefits compared to batteries. As the batteries have to be oversized about 300 times for a 2-second application, the installation price increases up to $60,000 – making ultracapacitors much more economical solution. They also have the benefit of being maintenance-free and having a very long lifetime.

1.5. Frequency regulation

Power grids have a nominal frequency value from which the actual value can drift due to differences in generation and load. Balancing the generation according to a highly variable load is a complicated task. It gets even more complicated if integrating renewables. Also, the starting process of large machinery usually requires very high peak current, which often results in an unacceptable voltage drop due to impedance in the power supply network. The voltage drop may affect equipment connected to the power supply network and can damage them irreversibly. Ultracapacitors can be used for frequency regulation to cover the short load peaks occurring due to such events (Figure 3). Their high power output, long cycle life, and maintenance-free service make them preferred candidates over batteries and flywheels.

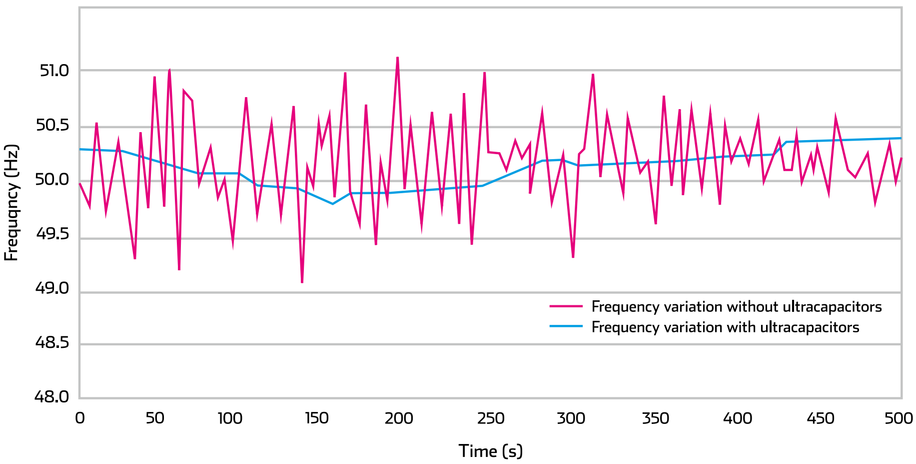

Fig. 3 Illustration of frequency variation with and without ultracapacitors.

2. The building blocks: ultracapacitors combined into SkelRack modules

2.1. The technology

Ultracapacitors are a fundamentally different technology when compared to batteries, fuel cells, or traditional engines running on combustible fuel. Ultracapacitors offer extremely high power density but store approximately 20 times less energy than batteries (Figure 4).

Ultracapacitors are highly efficient (over 95% in most applications) and can charge or discharge in less than 1 second, thus providing high power performance. However, many applications also require high energy density. Hence, ultracapacitors are often used in hybrid solutions, where energy comes from another source. In such a case, ultracapacitors cover peak power demands the other energy source is unable to cover, or can cover less efficiently and at considerable impact towards its lifetime. Also, batteries are not as cost-effective as standalone support as they would be when combined with ultracapacitors - batteries need to be oversized to support high power levels.

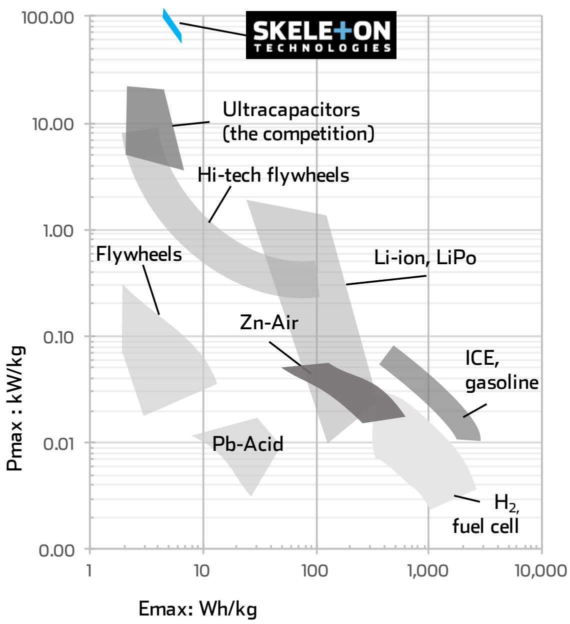

Fig. 4 The Ragone plot of different technologies.

The cost-effectiveness of ultracapacitors comes to the fore when a large number of charge-discharge cycles is required - batteries are limited to thousands of cycles while supercapacitors can manage 1 million cycles and more if their voltage is de-rated for a longer lifetime.

2.2. SkelRack modules

SkelGrid is an energy storage system comprised of 102V89F SkelRack modules. Every SkelRack module consists of 36 ultracapacitor cells and a control system that monitors and balances the cells. The module has an isolation barrier between the high voltage and the control side to increase the safety and performance of the communication system. The modules also include a CAN Bus 2.0B communication interface with configurable settings.

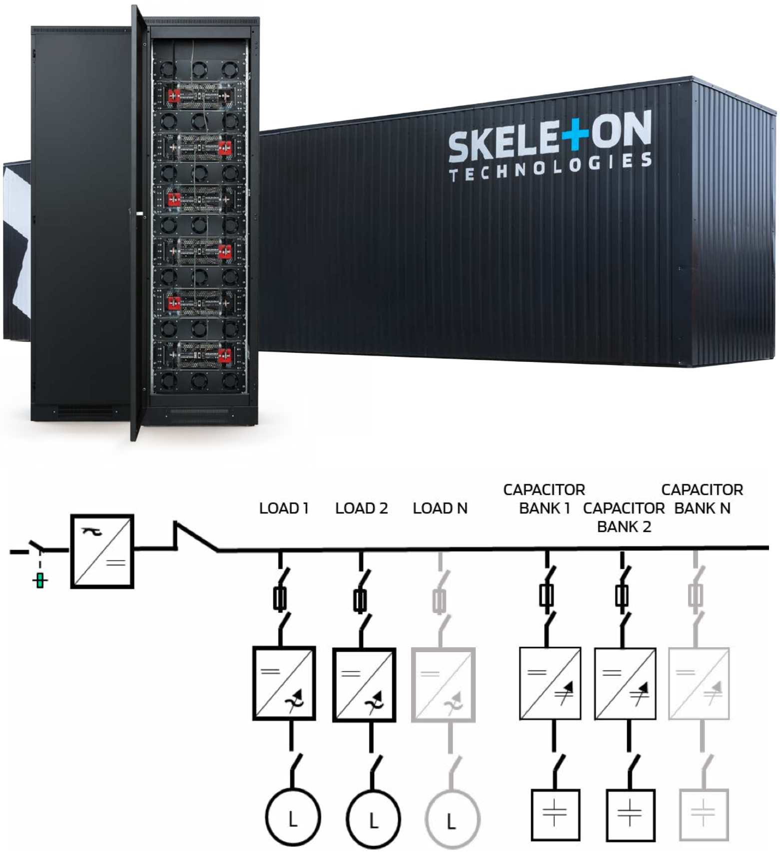

Fig. 5 Example scheme of capacitor banks and loads in drive application.

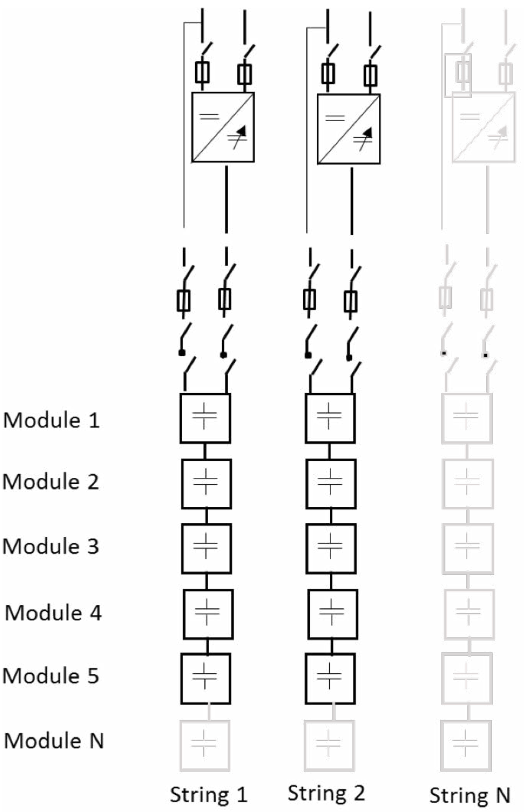

Fig. 6 The detailed scheme of capacitor banks in Figure 5.

To achieve the required power and voltage requirements, SkelRack modules can be connected in series (or in parallel), making these large ultracapacitor systems modular and very customizable. Figure 5 shows an example scheme of a commonly used setup for drive applications where the load(s) and capacitor bank(s) are connected to a common DC bus with an AC connection to generators.

To emphasize the modular nature and the practice of connecting several ultracapacitor modules in series and/or in parallel, the ultracapacitor part (capacitor banks) of the scheme above (Figure 5) could be presented in more detail, as shown in Figure 6. Every capacitor bank includes N individual modules connected in series, forming a string capable of reaching the required operating voltage.

3. SkelGrid systems

3.1. Cabinet sized SkelGrid

In brief, SkelGrid is a 19’’ 600 mm deep industrial switchboard enclosure for housing 6 SkelRack modules connected in series with integrated cooling panels, fuses, and switchgear in a separate enclosure of the same size. All SkelGrid models include the same amount of SkelRacks and thus, the same number of ultracapacitor cells. The individual models can be distinguished by the maximum power ratings, which range from 520 kW to 1500 kW. The specifications of the models are listed in the table below. The SkelGrid cabinet configurator is added to Appendix B.

Model	SkelGrid 1500	SkelGrid 1200	SkelGrid 1050	SkelGrid 520
Max power*	1500 kW	1200 kW	1050 kW	520 kW
Max current*	4900 A	4000 A	2500 A	1700 A
Nominal power**	380 kW	220 kW	150 kW	75 kW
Nominal current**	1250 A	750 A	500 A	250 A
Nominal voltage	612 V			
Efficiency at max power	74.3%	79.2%	81.7%	90.6%
Efficiency at nominal power	93.1%	95.9%	97.2%	98.6%
Modules in series	6			
Modules in total	6			
Cells in series	216			
Capacitance	14.8 F			

*Max power and max current are short period peak power and peak current.
**Nominal power and current are the rated values for the switchgear used in the system.

Table 1. SkelGrid models.

The main difference between the four SkelGrid models stems from the amperage rating of the wiring and contactors used. The system can be used at the nominal current rating until the maximum temperature (65ºC) of ultracapacitors is reached. The maximum current rating is approved for 10 seconds[3].

2 SkelRack module datasheet is given in Appendix A.

3 The wiring and the contactors can handle the elevated performance level in “normal operations”. Contactor malfunction may occur if the system is disconnected at maximum current levels.

3.1.1. Power vs. application time

Essentially, power is the rate at which electrical energy is being transferred. In the case of ultracapacitors, power is the measure of how quickly the cell can be charged-discharged. The duration of discharge sets limitations to maximum application time and is dependent on the energy stored, as well as the power applied. Generally, in case of the same nominal voltage, the usable energy will be the same and thus the power applied determines the duration of discharge, i. e., application time.

With 216 cells connected in series, the nominal voltage of all SkelGrid models is 612 V, and the total energy stored is 771 Wh. The amount of usable energy can be calculated according to the formula stated above, being 578 Wh for all the models. In case of the same number of cells and usable energy, the application duration depends solely on the power applied – the higher the power, the shorter the charge-discharge cycle. The application time is further shortened by losses, which increase exponentially the higher the power, leading to reduced efficiency. Application time and efficiency dependency on maximum power is demonstrated in Figure 7. In fact, at 1500 kW the discharge time is less than 0.5 s but stretches to over 25 seconds at 75 kW. Both slow (continuous cycling at low power, allowing long application times) and fast (high power, short application time) profiles can be applied to all four SkelGrid models (Table 2).

Model	Nominal voltage	Slow profile			Fast profile		
		Max power	Max current	Application time	Max power	Max current	Application time
SkelGrid 520	612 V	75 kW	250 A	26.79 s	520 kW	1700 A	3.78 s
SkelGrid 1050	612 V	150 kW	500 A	12.92 s	1050 kW	2500 A	1.06 s
SkelGrid 1200	612 V	220 kW	750 A	8.51 s	1200 kW	4000 A	0.82 s
SkelGrid 1500	612 V	380 kW	1150 A	4.53 s	1500 kW	4900 A	0.48 s

Table 2. Slow and fast profiles for SkelGrid models.

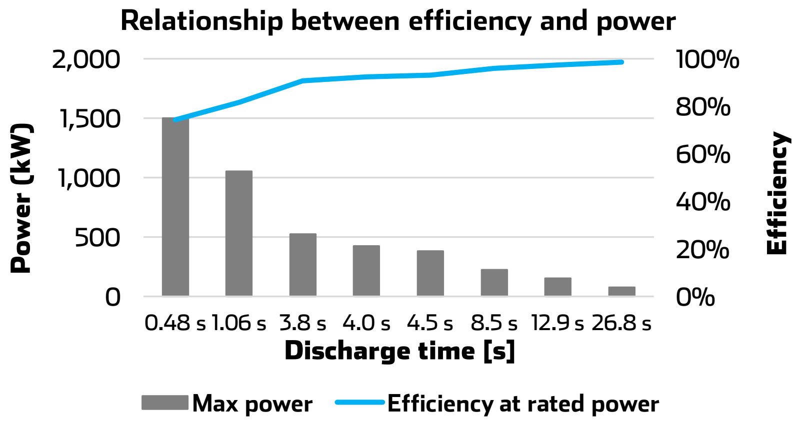

Fig. 7. Discharge time and efficiency dependency on maximum power.

3.1.2. Lifetime and working temperature

The working temperature has a direct influence on ultracapacitors' lifetime, which is why it must be considered. In general, the lifetime is shorter at higher temperatures. According to the Arrhenius law, increasing the cell temperature by 10 °C decreases its lifetime about 2 times.

The working temperature of ultracapacitors in a specific application can be calculated based on the average current I, the internal resistance[4] R_i and the thermal resistance R_{th}. The temperature change ΔT can be calculated as:

$$\Delta T = I^2 \times R_i \times R_{th}.$$

To obtain the actual working temperature of the device, the temperature change needs to be added to ambient temperature (or coolant temperature).

The dependence of ultracapacitors' lifetime on working temperature and voltage is shown in Figure 8 and Figure 9. It can be seen, that both higher voltage and temperature affect the lifetime negatively. Hence, in applications where higher temperature is unavoidable, a lower voltage can be used to obtain the same lifetime.

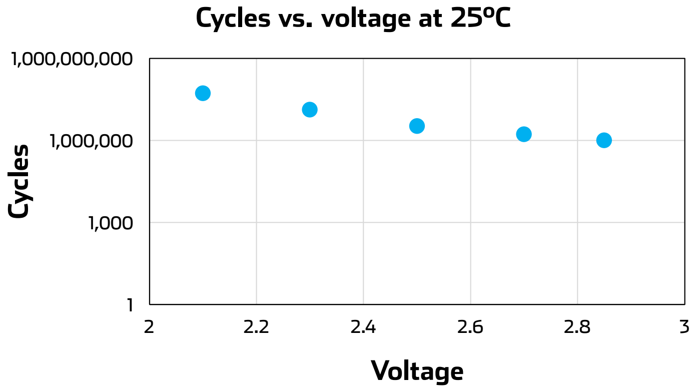

Fig. 8. Cycle life dependence on the operating voltage at 25°C.

While cycling continuously at high current ranges, the system will heat up, leading to a shortened lifetime.[5] The higher the ambient temperature, the more important it is to consider the heating effect during cycling. In the case of SkelGrid 1500 model, a single charge-discharge cycle at 1500 kW heats up the system by 5°C. Even with standard cooling and ambient temperature of 20°C, the system would reach the maximum operating temperature of 65 °C within 11 cycles.[6]

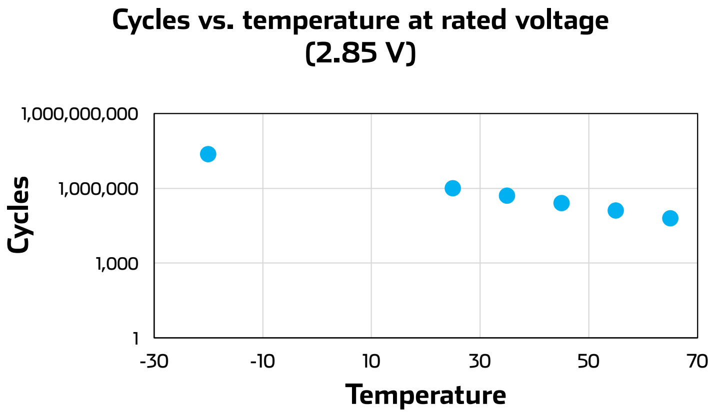

Fig. 9. Cycle life dependence on the working temperature at rated voltage.

Although SkelGrid can also be commissioned without cooling, the installed forced air cooling system should be used

4 Total resistance values should be used, obtained either from measurements according to IEC 62391 standard method 1B or 0.1 Hz AC test. 10 millisecond voltage drop test, the result of which is often quoted as nominal internal resistance, denominates contact resistance. Please see Skeleton Whitepaper on ESR for further details.

5 Lifetime is directly dependent on operating temperature and voltage. Operating temperature consists of ambient temperature and temperature rise during cycling. System cooling and voltage must be selected according to expected lifetime.

to lower the working temperature and enhance the system's lifetime. In this case, modules in SkelGrid are cooled with forced ambient air cooling – fans pushing the air through the whole enclosure. The cooling efficiency might be higher or lower Dependent on the ambient temperature of the room where SkelGrid is positioned. In extreme cases, an air-conditioned room is recommended to ensure proper cooling during heavy cycling.

In case forced air cooling is installed, the temperature resistance of modules varies between 0.15–0.165 °C/W at 20 °C ambient temperature. For non-cooled modules, the temperature resistance is much higher, which means a lower power rating will lead to the same temperature increase (Table 3).

ΔT	No cooling		Force-cooled	
	Power	Temperature resistance (at 20°C ambient)	Power	Temperature resistance (at 20°C ambient)
5 °C	22 kW	0.365 °C/W	35 kW	0.164 °C/W
15 °C	41 kW	0.321 °C/W	58 kW	0.160 °C/W
30 °C	63 kW	0.266 °C/W	83 kW	0.156 °C/W
40 °C	74 kW	0.259 °C/W	97 kW	0.152 °C/W

Table 3. Temperature resistance and power at various levels of ΔT for non- and force-cooled modules.

3.1.1. SkelGrid containers

The SkelGrid family also offers containerized solutions for achieving even higher power and voltage levels. The containerized SkelGrid operates at the megawatt level, offering extreme peak shaving solutions for massive power grids, and expanding the lifetime of the grid by protecting it from sudden, high power demand surges. SkelGrid containers can be assembled from SkelRacks in several ways to meet the exact application requirements. The modularity of the system gives a tremendous advantage of customizability. Additionally, a potential market for SkelGrid is hybridized systems, where ultracapacitor-based energy storage is combined with batteries. This will widen the range of possible applications and reduce both the CAPEX and OPEX dramatically. Also, so-called second-life batteries can be used (with 80% capacitance and 200% ESR) for the hybridized solutions, as the ultracapacitor unit will solve the issues of increased ESR and limited cycle life.

A SkelGrid container comprised of 168 SkelRack modules in total could supply peak power up to 60

6 It must be noted that the SkelGrid 1500 model should be only discharged at 4900A. During charging, the maximum system voltage of 612V cannot be exceeded. Charging current defines the size of the voltage drop once charging is stopped. If the system is charged with a higher current, there will be a larger voltage drop and more energy is lost. If the charging current is smaller or reduced before reaching 612V, the voltage drop will be smaller and more energy is stored. Hypothetically, cycling SkelGrid 1500 at 4900 A for 10 seconds will lead to 51 °C temperature rise. In short, SkelGrid 1500 main aim is to provide high power during discharge and should be charged at lower power rating.
SkelGrid 1050 can be cycled at rated power, however, 8% of energy loss due to the voltage drop must be considered. Also, the rated voltage of 612 V must not be exceeded, and the number of cycles is limited due to the temperature rise.

MW for 0.1 seconds. At lower peak power values, the application time increases, as shown in Table 4.

Peak Power [MW]	Discharge t [s]	Peak current [A]	Average current [A]
3	30.60	2801.11	1910.04
4	13.61	11203.95	7668.45
5	10.70	14004.94	9602.46
6	8.76	16805.84	11543.52
7	7.37	19607.15	13491.95
8	6.33	22407.11	15447.46
9	5.52	25208.44	17410.94
10	4.88	28011.33	19382.64
11	4.35	30812.96	21362.03
12	3.91	33611.19	23348.80
13	3.54	36409.54	25344.05
14	3.22	39209.40	27348.38
15	2.94	42015.40	29363.19
16	2.70	44818.62	31386.48
17	2.49	47620.54	33418.90
18	2.30	50412.84	35458.65
19	2.13	53218.76	37511.83
20	1.98	56024.19	39575.22
21	1.84	58825.55	41648.27
22	1.71	61620.63	43730.79
23	1.60	64415.51	45824.65
33	0.85	92401.29	67494.81
60	0.10	168670.74	139538.97

Table 4. Power and current values at different discharge times for SkelGrid container of 168 SkelRack modules.

Cost comparison of batteries and ultracapacitors in an example grid application (Figure 10) shows that the cost of batteries increases significantly with increasing C-rate. On the other hand, the price of ultracapacitors is not dependent on the C-rate in given range and stays around 0.5 M$ (estimation for 2021). Also, the higher the C-rate, the shorter the lifetime of a battery and replacements must be done more frequently. Ultracapacitors have a lifetime of 1 million cycles, meaning replacements are not necessary during the period. Thus, the total cost for given 1 MWh system in 2021 will be considerably lower for the ultracapacitor-based system compared to batteries when the average C-rate is higher than 1C.

the whole enclosure. The cooling efficiency might be higher or lower Dependent on the ambient temperature of the room where SkelGrid is positioned. In extreme cases, an air-conditioned room is recommended to ensure proper cooling during heavy cycling.

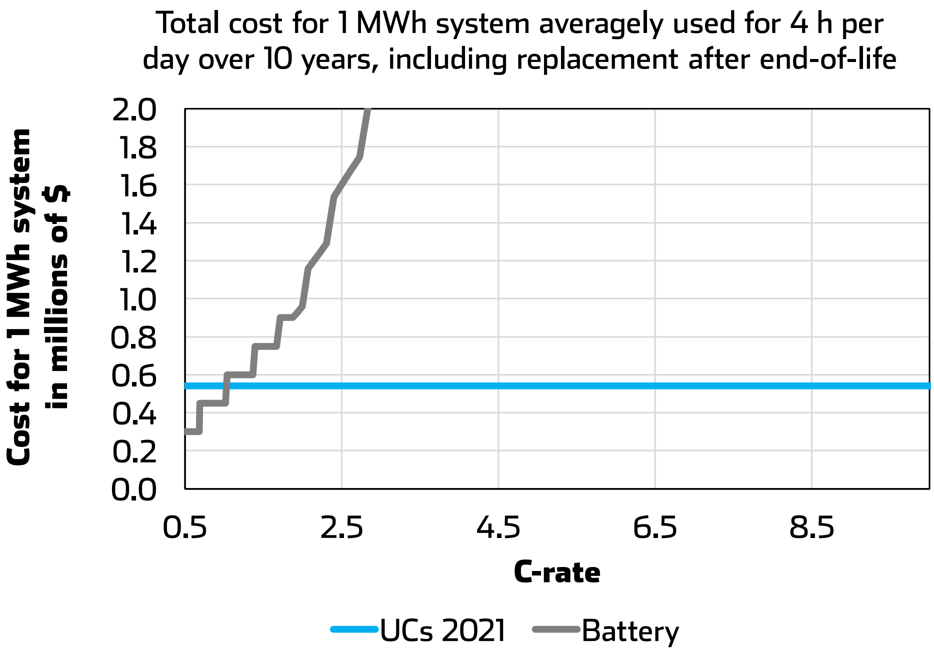

Fig. 10. Total cost comparison of batteries and ultracapacitors in 1 MWh application averagely used 4 h per day for 10 years, including replacement costs.

Appendix A

SkelRack 3.5U DATA SHEET

Technical specifications

Electrical

Nominal voltage	V	102
Absolute maximum voltage	V	108
Rated capacitance, initial	F	89
ESR (AC 0.1 Hz)	mΩ	5.9
ESR (DC 10 ms)	mΩ	4.8
ESR IEC	mΩ	5.5
Maximum serial voltage[10]	VDC	1 500
Maximum peak current (for 1 s duration)[1]	A	2 980
Short circuit current	kA	18.5
Maximum stored energy	Wh	128
Cells in total	#	36
Cell type	SCA3200	

Lifetime data*

Life at rated voltage and maximum operating temperature	hours	1 500
Projected cycle life at 25 ºC	cycles	1 000 000
Projected life at rated voltage and 25 ºC	years	10

Temperature

Operating temperature range		
Minimum	ºC	-40
Maximum	ºC	+65
Storage temperature range (uncharged state)		
Minimum	ºC	-40
Maximum	ºC	+70

Ultracapacitor management system

Nominal auxiliary supply voltage	24 V
Auxiliary supply voltage range	17-28 V
Auxiliary supply current	max. 0,25 A
Cell balancing method	Controlled active balancing
Temperature monitor	6 NTC sensors
Voltage monitor	Individual Cell
Communication interface	CAN bus 2.0B

Standards

International Protection Marking	IEC 60529, IP20
Isolation protection	EN 60664-1

Connectors

Power connector	Busbars
Signal connectors	D-sub DE-9 Male D-sub DE-9 Female
Connector location	Front

RACK MODULES	UNIT	102V-89F
Energy		
Energy[2]	Wh	128
Specific energy[3]	Wh/kg	4.5
Energy density[4]	Wh/L	4.3
Nominal power (calculated fomr ESR DC 10 ms)		
Nominal specific power (matched impedance)[5]	kW/kg	18.9
Nominal power density (matched impedance)[6]	kW/L	18.4
Practical power (calculated from ESR AC 0.1 Hz)		
Power (matched impedance)[7]	kW	443
Practical specific power (matched impedance)[5]	kW/kg	15.4
Practical power density (matched impedance)[6]	kW/L	15.0
Practical power (calculated from ESR IEC)		
Power (matched impedance)[7]	kW	472
Practical specific power (matched impedance)[5]	kW/kg	16.4
Practical power density (matched impedance)[6]	kW/L	16.0
Thermal parameters		
Thermal resistance (R_{ca})[8]	°C/W	0.17
Thermal capacitance (C_{th})	kJ/°C	30.6
Maximum continuous current (ΔT 15 °C)[9]	A	131
Maximum continuous current (ΔT 30 °C)[9]	A	187
Maximum continuous current (ΔT 40 °C)[9]	A	218
Physical parameters		
Typical mass	kg	28.8
Typical volume	L	29.6
Depth max	mm	502
Width max	mm	480
Height	mm	155

**Capacitance decrease 20% from initial value; resistance increase 100% from initial value.*

1 $\text{Maximum peakcurrent (1s)} = \frac{\frac{1}{2}CV}{C \times ESR + 1s}$

2 $E_{stored} = \frac{\frac{1}{2}CV^2}{3600}$

3 $E_{max} = \frac{\frac{1}{2}CV^2}{3600 \times mass}$

4 $E_{max} = \frac{\frac{1}{2}CV^2}{3600 \times volume}$

5 $P_{max} = \frac{V^2}{4 \times ESR \times mass}$

6 $P_{max} = \frac{V^2}{4 \times ESR \times volume}$

7 $P_{max} = \frac{V^2}{4 \times ESR}$

8 $R_{th} = \frac{\Delta T}{ESR \times I^2}$

9 Maximum continuous current measured with airflow of 90 CFM over the top and bottom plates of the module

10 Pollution degree 2 has to be achieved by reducing possibilities of conductive dust and condensation or high humidity at the creepage distance, through the provision of ventilation and heating.

Standard markings

+ Name of Manufacturer, Part number, Serial number, Rated voltage
+ Rated capacitance, Negative and positive terminals, Warning marking
+ Total energy in watt-hours
+ Electrolyte material used

Notes

+ Testing instructions available on www.skeletontech.com
+ All information provided on this data sheet and all subsequent ultracapacitors sales and testing are subject to Standard Terms of Service (ToS) available on www.skeletontech.com, document *General Terms of Sale for Skeleton Technologies OÜ*
+ For ultracapacitors, the power values are often calculated using nominal resistance values (DC 10 ms or AC 0.1 Hz). For engineering purposes, practical values based on total resistance are preferred.

Appendix B

The SkelGrid system can be configured according to the table below.

Model			
0150	0120	0105	00520
SGS1500	SGS1200	SGS1050	SGS0520
Module			
A			
SMR102089A			
Configuration			
A	**B**	**C**	**D**
Enclosure: 2200 x 1400 x 600 mm + Main switch, fuses and additional contacts + Additional contacts include (all contacts are potential free contacts): + State of the auxiliary supply (auxiliary supply is included in the system and is needed to power up CAN network) + Main switch position + Discharge switch position + Main contactor position + Ultracapacitor energy storage compartment side door position + Cooling ventilator supply state (on/off) + Main contactor + CAN connection between SkelRack modules + Discharge resistor + Bus bars to main switch	Same as option A, excluding: + Main contactor + Potential free contact, which indicates the position of the main contactor	Same as Option B, excluding: + Discharge resistor + Discharge switch + Potential free contact, which indicates the position of the discharge switch	Enclosure: 2200 x 600 x 600 mm + CAN connection between SkelRack modules + Bus bars to main switch
IP rating			
1	2	3	4
IP20	IP32	IP43	IP54
Color			
1			
RAL 9005			
Cooling			
1	2		
Cooling available	No cooling		

Table 5. Cabinet sized SkelGrid configurator

Note that the system designation for cabinet sized SkelGrid is SGS. An example configuration of SGS 0150-A-A-3-1-2 would refer to a 1500 kW model based on SMR102089A module, including everything listed in option A, with a IP rating of IP43 and color RAL 9005.