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Dimensioning and Grid Integration of Mega Battery Energy Storage System for System Load Leveling

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Abstract--**In countries without hydropower potential, Peak load and spinning reserve have to be entirely covered by thermal generation. The corresponding environmental and economic burden is increasing on and on. This paper discusses how using mega Battery Storage Energy System (BESS) for system load leveling can mitigate the problem, and to which extent. Limitations on peak shaving of load profiles with flat and long peak are identified and quantified. It proposes a simple empiric method for dimensioning the capacity of mega BESS connected to primary substations (S/S) with loads. The method is based on detailed load following operation calculations performed for the United Arab Emirates. The concepts of S/S peak inversion and reduced S/S firm capacity are introduced. Finally, simplified scheme for grid integration of mega BESS to S/S without loads is proposed.**

Index Terms— **Batteries, energy storage, load leveling.**

I. Introduction

New technologies in Battery Energy Storage Systems (BESS) could in a near future deny the cliché that energy cannot be stored in large amount. Engineers are indeed confronted with this annoying constraint since the birth of the power sector. An adverse consequence is that networks have to be dimensioned for a safe load supply during peak load hours, which occur a few hours a day for a few months only. For the rest of the year, the networks are well oversized.

Load leveling can mitigate the problem. Cheap excess base load capacity is stored during low load conditions and released during peak hours, reducing expensive power generation. For decades, pumped storage hydroelectricity was the solely practical solution. Unfortunately, appropriate sites are limited in number. Some countries even do not have any site. This is especially the case for countries without hydroelectricity potential, like the United Arab Emirates (UAE).

In countries without hydroelectricity potential, covering the peak load demand is excessively expensive (install capacity investment and operation costs), because it has to be entirely produced by thermal units. Spinning reserve requirements worsen the problem, because it has also to be produced by thermal units. The burden on the environment and the economy is heavy.

Until recently UAE strategy was to invest in combined cycle units, which are there the cheapest thermal solution. But with the outstanding economy growth in the region the power sector can barely follow the move and new capacity installation reaches unprecedented highs [1].

It clearly appears to the UAE authorities that alternative solutions have to be found. A quick overview of the situation allows drawing up that one unique technology will not be able alone to mitigate the problem. Recently several projects were initiated, and some of them are already under implementation. To name the majors: demand side management (DSM), distributed generation, smart grid, renewable energy, distributed BESS and centralized BESS. BESS solution was addressed quite recently and benefits from new battery and power conversion system (PCS) technologies that are now mature and available on the market [2].

BESS are here classified into two categories: distributed systems and centralized systems.

Distributed BESS are big systems (≥ 1 MW) aiming to improve the system and reduce the costs at medium voltage (MV) system level (local load leveling, renewable energy storage, power quality, back-up supply during grid disconnection, reliability improvement, upgrades deferral, etc.) [2-4]. Charge and discharge strategy complies with local constraints and objectives. Almost all existing systems fall under this category.

Centralized BESS on the contrary are much bigger systems (≥ 20 MW), i.e. mega systems, aiming to support the HV grid, by reducing the system peak load thanks to large-scale load leveling and/or by participating to spinning reserve. The two world largest centralized systems are found in Fairbanks, Alaska, USA (40 MW for 7 minutes – only spinning reserve) and in Japan for the Rokkasho 51 MW Wind Farm (34 MW for 7.2 hours).

Both types can also offer additional functions like area regulation, long line stabilization, power factor correction, frequency regulation, voltage control, black start capability, carbon emissions reduction, etc. [4-8]

This paper is focused on large-scale load leveling, which is the main objective of BESS installation in UAE. Other functions are also considered as additional benefits for the

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country but are not discussed here. They includes spinning reserve participation (except when the system is discharging at full capacity), and in a less extent frequency regulation and voltage control.

In Section II the use of mega BESS for full system load leveling is presented. Limitations on peak shaving for flat and long peak are identified and quantified in Section III. Section IV proposes a method for dimensioning the capacity of mega BESS connected to primary substations (S/S) with loads. Section V and VI introduce respectively the concepts of S/S peak inversion and reduced S/S firm capacity. Section VII describes the grid integration of mega BESS to S/S without loads. Finally Section VIII qualitatively presents the benefits of load leveling.

II. System Load Leveling

Like any large-scale energy storage system, a mega BESS allows storing cheap base-load energy produced typically at night and releasing it during peak hours, every day. The resulting modified load profile is flattened, the load factor increases and the peak load is shaved.

TABLE I
LOAD PROFILE CHARACTERISTICS

Profile Name		Profile 1	Profile 2
Peak Duration		< 6h	> 8h
Peak Load	MW	5.000	5.000
Bottom Load	MW	3.000	3.920
Load Factor	p.u.	0,75	0,90
Demand	MWh	89.900	107.927

BESS installed capacity required for completely even out the system load depends on the load profile (Table I), the efficiency and charging/discharging characteristics of the battery system.

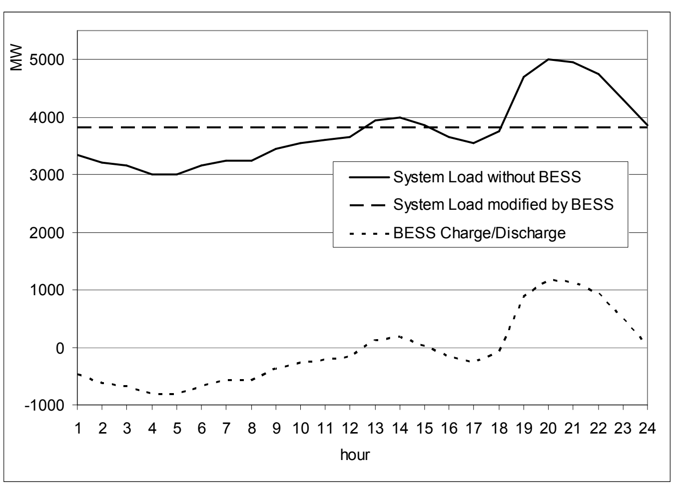

Fig. 1. System load leveling – Profile 1

Given a daily system load profile, the maximum BESS capacity B_{max} is reached when the modified load profile is completely flat. Peak shaving equals the BESS capacity when the peak is sharp and lasts only a few hours (Fig. 1). On the contrary, if the peak load is flat and lasts for many hours (Fig. 2), the BESS capacity is dimensioned for the charge and the peak shaving is smaller. Profile 1 is taken from an African country. Profile 2 is taken from an Emirate.

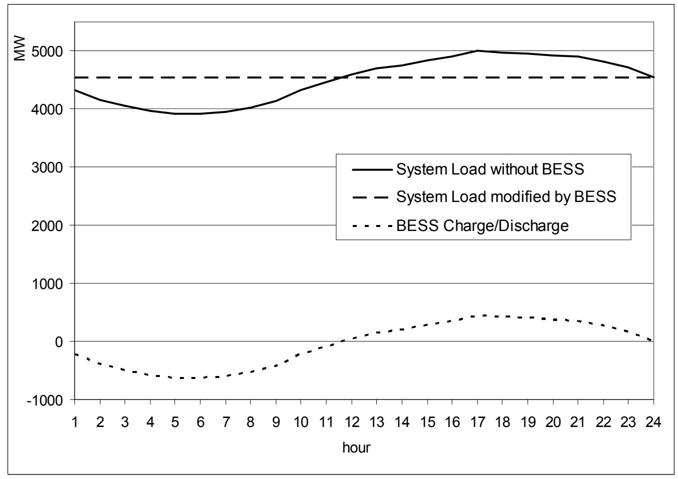

Fig. 2. System load leveling – Profile 2

Load following operation (LFO) simulation [9] are performed with a charging/discharging efficiency factor of 73%. About 8 and 5% of the load demand have to be stored in the BESS respectively for Profiles 1 and 2. Corresponding peak shaving comes to 24 and 9% (Table II). These figures show the interest of BESS, especially for load profiles with a sharp and short peak.

TABLE II
LOAD LEVELING RESULTS

Profile Name		Profile 1	Profile 2
BESS Cap.	MW	1180	630
B_{max}	% of peak	23.6	12.6
Max. BESS	MW	820	630
Charge	% of peak	16.4	12.6
Max. BESS	MW	1180	450
Discharge	% of peak	23.6	9.0
	% of BESS cap.	100	72
BESS load	MWh	6750	4791
(inc. loasses)	% of load	7.5	4.4
Load Demand	MWh	4970	3518
Shaving	% of load	5.5	3.3
Charge	h	15	12
Discharge	H	9	12
Efficiency	%	73.6	73.4

III. Peak Shaving

When the BESS capacity is much smaller than the load, one MW of installed capacity exactly results in one MW of peak shaving. For load profiles with a sharp peak, this linear relation is maintained until reaching full load leveling. For load profiles with a flat peak lasting for many hours, the relation is not linear beyond a certain BESS capacity value B_{lim}.

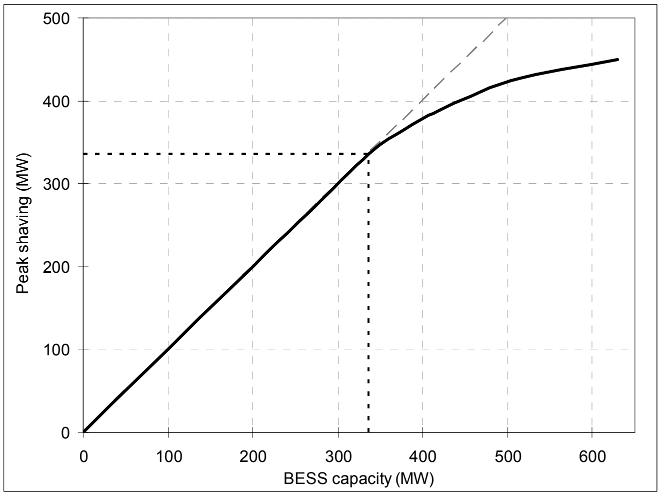

Fig. 3. Peak shaving (MW) vs. BESS capacity – Profile 2

Beyond this point, the energy that can be charged is not sufficient to balance the losses and the energy to be discharged for load leveling. It is due to the long discharging period and the small power difference between low and peak load. Discharged energy has then to be reduced. One can limit the discharge period or reduces the discharge output power on the whole discharge period. The second solution is chosen because it results in a uniform peak shaving. LFO simulations for profile 2 show that the reduction equals 72% for the complete load leveling (Fig. 3).

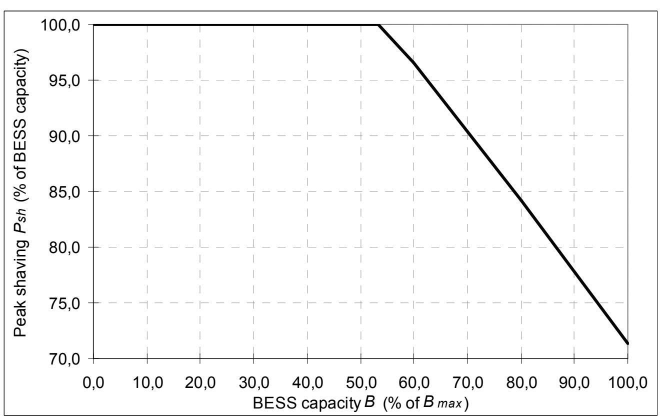

Fig. 4. Peak shaving (%) vs. BESS capacity – Profile 2

LFO simulations performed for various BESS capacity levels show that the relation between peak shaving P_{sh} (in percent of BESS capacity) and the BESS capacity B (in MW or in percent of its maximum B_{max}) is linear (Fig. 4):

$$P_{sh} = a \cdot B + b \;\; for \;\; B_{\lim} \leq B \leq B_{\max}$$

The relation is independent of the absolute peak load value. For Profile 2, a = -0.61 and b = 133. At P_{sh} = 100%, $B = B_{lim}$ = 54% of B_{max}. It corresponds to 6.8% of the peak load, i.e. about 70 MW of BESS per GW of peak load. Such a figure corresponds to mega BESS.

IV. BESS Capacity Dimensioning in S/S with Loads

Mega BESS considered in UAE comprises several BESS blocks. Each block (Fig. 5) is composed by a large number of battery cells grouped in series into parallel strings. Several strings are connected in parallel to a common DC bus connected to a PCS. At their turn, Several PCSs are connected in parallel to a common AC bus. Finally a step-up transformer connects the AC bus to the grid. The HV side of the transformer is the grid terminal of the corresponding BESS block.

The number of strings and of PCS put in parallel, as well as the power ratings and the nominal voltages of major BESS components – batteries, PCS, transformers – depends on the chosen battery and PCS technology (maximum string voltage, maximum number of parallel strings, PCS AC and DC voltages), the objective of the project (stored energy for load leveling, peak shaving, grid AC voltage) and available equipments on the market.

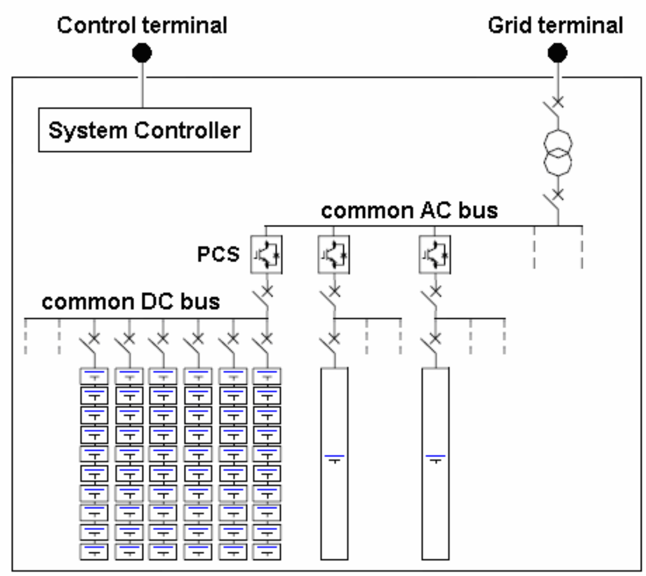

Fig. 5. Generic single-line diagram of one BESS block

Each block comprises a control system, which integrates all specific control sub-systems (battery modules, PCS, transformer, AC and DC circuit breakers, etc.) A central control system pilots the control systems of the blocks composing the mega BESS. On a communication and control point of view the BESS then acts like a single unit.

A mega BESS is thus seen by the grid as a single controllable power unit but with several grid terminals, that can be connected to the same S/S or geographically distributed. Network integration study has then to fill the gap between the BESS terminals and the grid, by choosing appropriate locations (space and spare feeders availability, S/S load and firm capacity, etc.)

An Emirate's network comprises about fifty HV/MV primary S/S (HV: 220 or 132 kV – MV: 11 or 33 kV). Connecting mega BESS blocks to a S/S is feasible by simply connecting with cables each block terminal to a MV feeder of the S/S. Such a grid connection is possible at the condition that enough spare feeders are available or that substation extensions are possible, and that enough space for the BESS is available close the S/S. Because of the large footprint of a BESS, the last condition could be difficult to fulfill, especially for existing S/S in already developed areas.

TABLE III
α_{BOTTOM} AND α_{LP} CALCULATIONS RESULTS

α_{bottom}	Rural areas	0.4 to 0.6
	Industrial areas	0.7 to 0.8
	Cities	0.6 to 0.7
α_{LP}		-20 to 20%

The maximum S/S power transfer from the HV grid to its MV side equals the firm capacity of the HV/MV transformers P_{firm}. In UAE, P_{firm} is defined with N-1 contingency criteria and a load factor between 0.85 and 0.9 depending on the loads type.

Maximum BESS capacity in an S/S with loads B_{firm} is limited during charging period by the difference between P_{firm} and the bottom load P_{bottom} (Fig. 6). Detailed LFO calculations are performed for every S/S. Analysis of the results allows obtaining the following simple empiric equation:

$$B_{firm} = P_{firm} \cdot (1 - \alpha_{bottom}) \cdot (1 + \alpha_{LP})$$

where $\alpha_{bottom} = P_{bottom} / P_{firm}$ and α_{LP} is a correction factor that takes into account the BESS charging/discharging characteristics and the load pattern. The factors α_{bottom} and α_{LP} are calculated for all S/S. Table III presents typical values.

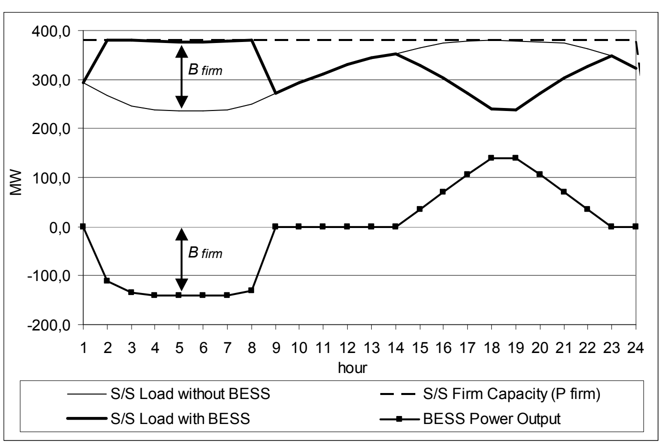

Fig. 6. Substation peak inversion 1 – BESS capacity = B_{firm}

This empiric method allows easily estimating the maximum BESS capacity that can be installed in a S/S with loads, without requiring detailed LFO simulations. The biggest S/S in UAE are installed with four 220/33 kV 140 MW transformers offering a firm capacity of 380 MW. Given a typical value of α_{bottom} = 0.6 and a conservative value of α_{LP} = -5, maximum BESS capacity B_{firm} is then about 140 MW.

V. SUBSTATION PEAK INVERSION

Hourly simulations for a BESS with an installed capacity equals to B_{firm} and connected to a S/S with loads are presented in Fig. 6 and 7. They present two different discharge strategies.

The S/S load profile with BESS is characterized by a peak occurring during system low loads (at night) and a low load taking place during system peak load hours. The S/S peak and low loads are inverted. The S/S with BESS contributes to system load leveling. This behavior is called substation peak inversion.

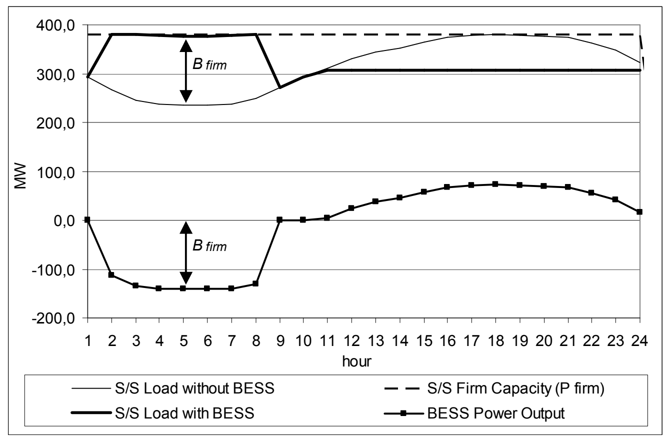

Fig. 7. Substation peak inversion 2 – BESS capacity = B_{firm}

VI. REDUCED SUBSTATION FIRM CAPACITY

Consider a BESS connected to a S/S with loads with an installed capacity B greater than B_{firm}. In order to comply with N-1 contingency on an event on one of the HV/MV transformers, the firm capacity available for the loads of the S/S has to be reduced (Fig. 8).

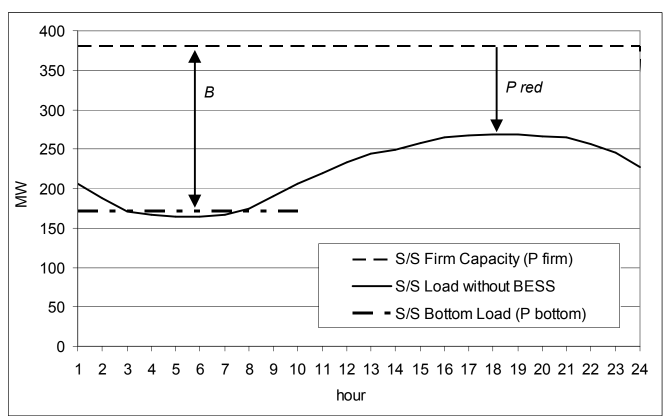

Fig. 8. Reduced firm capacity P_{red}

As for B_{firm}, an empiric equation allows estimating the reduced firm capacity P_{red}:

$$P_{red} = \frac{P_{firm} - \dfrac{B}{(1+\alpha_{LP})}}{\alpha_{bottom}}$$

Given B = 300 MW, P_{firm} = 380 MW and the typical values of α_{bottom} and α_{LP} given here above, then P_{red} falls down to around 110 MW, that is a reduction of 270 MW. In this case, S/S peak inversion is much significant and therefore system load leveling contribution is bigger (Fig. 9).

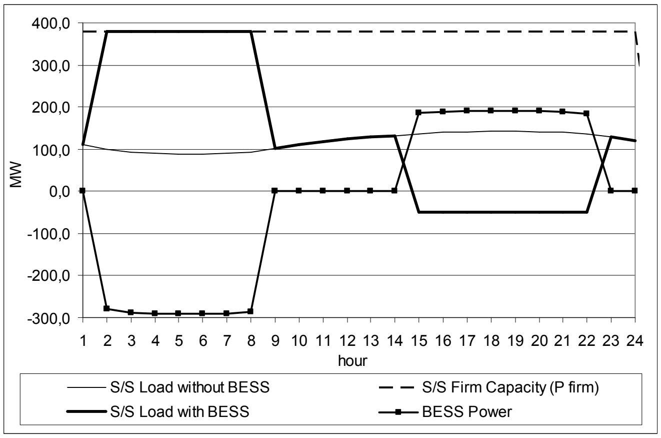

Fig. 9. Substation peak inversion – BESS capacity > B_{firm}

VII. BESS Connection to S/S without Loads

Maximum BESS capacity B_{firm} or reduced firm capacity P_{red} constraints do not apply if the system is connected to a S/S without loads. In this case, the S/S firm capacity is fully available for the BESS. Practically a new S/S is build only for BESS grid integration.

As explained above, an original characteristic of mega BESS is that it is a single controllable power unit but with several MV terminals. A main advantage of having several terminals is the increased reliability compared to a single terminal. Thanks to an adapted design, N-1 event is limited to the loss of a single block (typically several tens of MW), all the other ones staying on-line (hundreds of MW in total). It makes a mega BESS extremely reliable.

Fig. 10 schematically displays an example of possible connection at 33 kV of a 200 MW BESS to a S/S without loads. The BESS is composed of ten blocks of 20 MW each. The corresponding 20 terminals are distributed among three double bus bar sections. Each section is supplied by a 220/33 kV 140 MVA transformer. All equipments are standards ones used in typical S/S in UAE. This scheme completely satisfies N-1 reliability constraints (transformers, section bus bars and lines). The worst N-1 event is the loss of a 20 MW block, i.e. 10% of the installed capacity of the whole system.

The big advantage of this solution compared to the connection to S/S with loads is the freedom for choosing BESS location. Such a system can be installed almost anywhere along the HV network, while for S/S with loads, enough space has to be available close to the S/S.

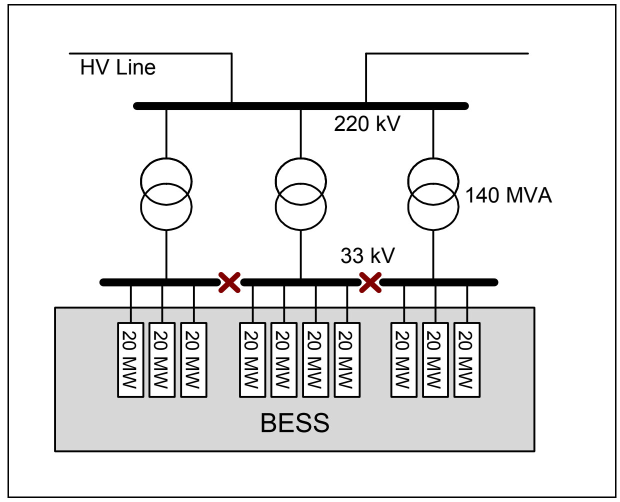

Fig. 10. Example of a 200 MW BESS in a S/S without loads

VIII. Load Leveling Benefits

In UAE, base load is produced by combined cycle units, which produce the cheapest possible electricity in a country without hydropower potential. And peak load is generally covered by backup fuels (crude oil, gas oil, fuel oil), which are up to five to six times more expensive than natural gas.

With such a fuel cost difference, load leveling can help to reduce system production costs, even with an efficiency factor of 70 to 75%. By also taking into account the generation deferral, including the corresponding operation and maintenance costs reduction, the benefits are then sufficient to justify the investment of mega BESS in UAE.

Thanks to lower CO_2 emissions with combined cycle than with backup fuel, about 0.35 Tons of CO_2 can be saved for each produced MWh. Trading these emissions savings on a market like the European Union Emission Trading Scheme (EU ETS) [10] increases the BESS benefits by about 0.5 to 1%.

IX. Conclusion

This paper provides examples of mega BESS dimensioning for full system load leveling. Limitations on peak shaving for load profiles with flat and long peak is identified and quantified. Empiric methods for maximizing the use of firm capacity of HV/MV substations with or without loads for BESS dimensioning are also proposed. In order to do so, the concepts of S/S peak inversion and reduced S/S firm capacity are introduced.

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XI. Biographies

Gauthier Dupont is the Power Systems Studies Manager of MVV decon GmbH in Bad Homburg, Germany. He is involved in innovative planning projects like BESS, especially in the UAE. He received a M.Sc. in Physics (1994) and Geophysics (1995) at the Université Libre de Bruxelles, Belgium.

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