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Hybrid energy storage systems for renewable energy applications

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Abstract

The paper gives an overview of the innovative field of hybrid energy storage systems (HESS). An HESS is characterized by a beneficial coupling of two or more energy storage technologies with supplementary operating characteristics (such as energy and power density, self-discharge rate, efficiency, life-time, etc.). The paper briefly discusses typical HESS-applications, energy storage coupling architectures, basic energy management concepts and a principle approach for the power flow decomposition based on peak shaving and double low-pass filtering. Four HESS-configurations, suitable for the application in decentralized PV-systems: a) power-to-heat/battery, b) power-to-heat/battery/hydrogen, c) supercap/battery and d) battery/battery, are briefly discussed. The paper ends with a short description of the HESS-experimental test-bed at Chemnitz University of Technology.

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*Keywords:*hybrid energy storage; battery; supercap, hydrogen; control; energy management; photvoltaics; power-to-heat

1. Introduction

The global problems of a rapidly rising CO_2-concentration in the atmosphere, the green-house effect and the related severe changes in world surface temperature and world climate have to be addressed and solved quickly. One important part of the solution will be a fast transition from the antiquated fossil-based energy system to a sustainable, 100%-renewable energy system. Therefore, a further and fast dissemination of PV and wind power is required. PV and wind power fluctuations on an hourly, daily and annual time scale (and with a regional distribution) can be handled, employing a variety of flexibility technologies, such as demand side management, grid extension or energy storage [1]. A number of storage technologies based on electrical, mechanical, chemical and thermal energy storage

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principles are available with quite different technical parameters and operating characteristics (s.Tab.1, [1], [2], [3]). Current system analysis studies indicate energy storage demand on a short-, mid- and long-term time scale [4], [5]. At this point, the utilization of the hybrid energy storage system (HESS) approach, integrating storage technologies with supplementary operating characteristics, can be very beneficial. Section 2 discusses typical HESS-applications, energy storage coupling architectures and basic energy management concepts. Section 3 introduces a principle power flow decomposition approach based on peak shaving and double low-pass filtering. Four HESS-configurations, suitable for the application in decentralized PV-systems: a) power-to-heat/battery, b) power-to-heat/battery/hydrogen, c) supercap/battery and d) battery/battery, are briefly discussed. The paper ends with a short description of the HESS-experimental test-bed at Chemnitz University of Technology.

Table 1.Comparison of different energy storage technologies.

	supercap	SMES	flywheel	lead-acid	lithium-ion	NaS	redox-flow	hydrogen	pumped hydro	CAES
energy density in Wh/l	2-10	0,5-10	**80-200**	50-100	**200-350**	**150-250**	20-70	**750/250bar 2400/liquid**	0,27-1,5	3-6
installation costs in €/kW	**150-200**	high	300	**150-200**	**150-200**	**150-200**	1000-1500	1500-2000	500-1000	700-1000
installation costs in €/kWh	10000-20000	high	1000	**100-250**	300-800	500-700	300-500	**0,3-0,6**	**5-20**	**40-80**
reaction time	**<10ms**	**1-10ms**	**>10ms**	**3-5ms**	**3-5ms**	**3-5ms**	>1s	10min	>3min	3-10min
self-discharge rate	up to 25% in first 48h	10-15 %/day	5-15 %/h	0,1-0,4 %/day	**5 %/month**	10 %/day	0,1-0,4 %/day	**0,003-0,03 %/day**	**0,005-0,02 %/day**	0,5-1 %/day
cycle life-time	**>1Mill.**	**>1Mill.**	**>1Mill.**	500-2000	**2000-7000**	**5000-10000**	**>10000**	>5000		
life-time in years	15	20	15	5-15	5-20	15-20	10-15	20	**80**	ca. 25
system efficiency in %	77-83	**80-90**	**80-95**	70-75	**80-85**	68-75	70-80	34-40	75-82	60-70
short-term (<1min)	**XXX**	**XXX**	**XXX**		X		X			
mid-term (>1min,<2d)			X	**XXX**	**XXX**	**XX**	**XX**	X	**XX**	**XX**
long-term (>2d)				X		X	**XX**	**XXX**	**XXX**	**XX**

2. Hybrid energy storage systems

In a HESS typically one storage (ES1) is dedicated to cover “high power” demand, transients and fast load fluctuations and therefore is characterized by a fast response time, high efficiency and high cycle lifetime. The other storage (ES2) will be the “high energy” storage with a low self-discharge rate and lower energy specific installation costs (s.Tab.1 and Fig.1).Main advantages of a HESS are:

- reduction of total investment costs compared to a single storage system (due to a decoupling of energy and power, ES2 only has to cover average power demand)
- increase of total system efficiency (due to operation of ES2 at optimized, high efficiency operating points and reduction of dynamic losses of ES2)
- increase of storage and system lifetime (optimized operation and reduction of dynamic stress of ES2)

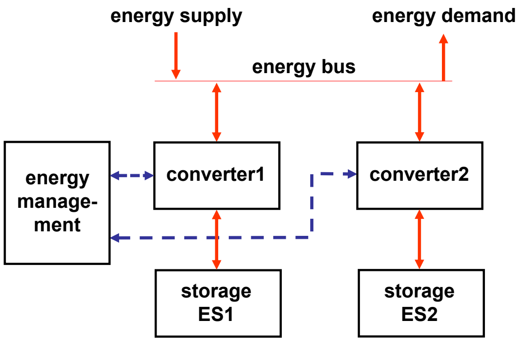

Fig. 1.Basic structure of a HESS.

2.1. Overview of HESS-applications

Results of a literature review indicate quite a number of promising HESS-applications, e.g.:

- HESS in hybrid and fuel cell powered electric vehicles (supercap/battery-HESS [6], [7], [8], [9] or battery/fuel cell-HESS [10], [11])
- HESS-applications in renewable autonomous energy supply systems mainly based on a battery/hydrogen-combination [12], [13], [14], [15], [16]
- grid-connected HESS on a household [17], district or regional level (e.g. lithium-ion/redox-flow battery application for the island Pellworm [18])
- HESS for large scale wind- and PV-park power management [19], [20]
- other specific HESS-configurations, e.g. SMES/battery-HESS [21], CAES/battery-HESS [22] and flywheel/battery-HESS [23]

Batteries, particularly lithium-ion batteries, play a key role in many HESS-applications. They can be utilized both as the “high energy” or the “high power” storage. Supercaps and flywheels are characterized by even higher power densities, efficiencies and cycle lifetimes compared to batteries. Redox-flow batteries are a promising technology due to their storage immanent decoupling of power and stored energy (similar to the hydrogen and power-to-gas storage path) and due to their good cycle lifetime and recycling capability. Renewable hydrogen (H_2) and methane (CH_4) are both very promising options for long-term energy storage. Also heat storage and power-to-heat concepts will gain importance in the context of future HESS-applications. The storage of heat produced from excessive renewable energy (via electric heating cartridges or heat pumps) and from power-to-gas conversion processes (e.g. electrolyser or fuel cell) will increase the overall utilization rate of renewable energies. Moreover, power-to-heat will enable HESS to perform peak shaving and hereby significantly reduce the stress for the other storage components and for the public grid. Optimizing design, control and energy management strategies for HESS at the interface between electricity, heat and gas sector will play an important role and will unfold significant potentials for further improvements of cost, efficiency and lifetime of renewable energy systems.

2.2. Energy storage coupling architectures in HESS

There are different ways for the coupling of the energy storages in a HESS. A simple approach is the direct DC-coupling of two storages. Main advantage is the simplicity and cost-effectiveness. Moreover, the DC-bus voltage experiences only small variations. Main disadvantage is the lack of possibilities for power flow control and energy management and a resulting ineffective utilization of the storages (e.g. in a supercap/battery-HESS with direct coupling only a small percentage of the supercap capacity can be utilized when operated within the narrow voltage band of the battery). The second energy storage coupling architecture in a HESS is via one bidirectional DC/DC-converter. The converter can either be connected to the "high-power" or to the "high-energy" storage. In the latter case the "high-energy" storage can be protected against peak power and fast load fluctuations. The DC/DC-converter then operates in current-controlled mode. A drawback of this solution is the fluctuation of the DC-bus voltage, which is identical to the voltage of the "high-power" storage. The third and most promising coupling architecture consists of two DC/DC-converters. Here the parallel converter topology (s.Fig.1) is very common. The additional DC/DC-converter associated with the "high-power" storage is in charge of the voltage regulation of the DC-bus. It helps to operate the "high-power" storage in a broader voltage band, and hereby the available storage capacity is better utilized. Besides the parallel converter topology also a serial, cascade-type of converter topology is possible, which is generally more expensive and more difficult to be controlled. Disadvantages of the two converter coupling architecture are higher complexity and slightly higher costs. There are isolated and non-isolated DC/DC-converter topologies available for HESS-applications (e.g. buck/boost, half-bridge, full-bridge) with the trend to highly efficient and cost effective multi-port converters with a reduced number of conversion stages [24].

2.3. Control and energy management concepts for HESS

An intelligent control and optimizing management of the power flow distribution is essential for a good operation of any HESS. Quite a number of different control and energy management concepts has been studied, mostly in the field of hybrid and fuel cell electric cars. Fig.2 gives an overview of the basic classes of HESS-energy management concepts.

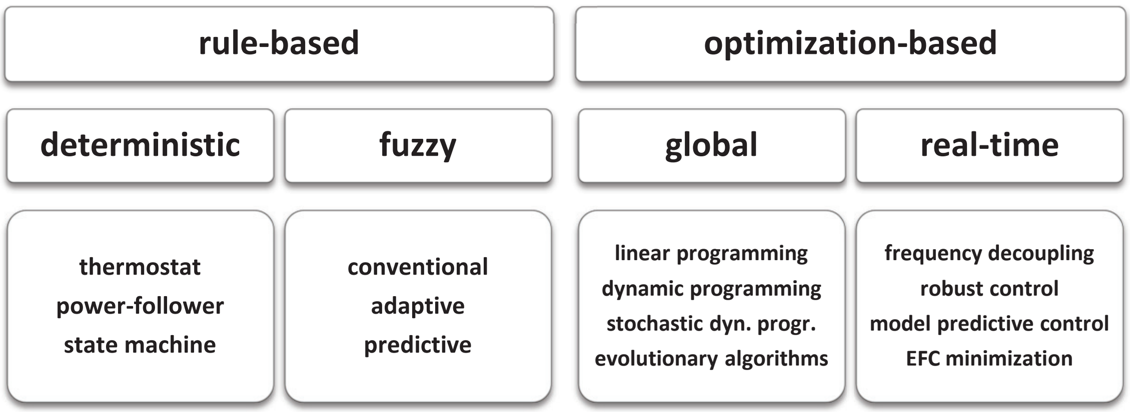

Fig. 2.Control and energy management concepts for HESS.

Generally two classes, rule-based and optimization-based energy management concepts, can be distinguished. Rule-based concepts are well suited for real-time applications. The rules are created by an expert or mathematical models. A simple rule-based control strategy for HESS is the "thermostat"-concept. The "high energy" storage ES2 is switched on and off according to a lower and an upper SOC-threshold applied to the "high power" storage ES1. A more advanced concept is based on state machine control [25], which can involve multiple rules (to be defined on the basis of heuristic or expert experience). A further improvement of the rule-based concept is fuzzy logic control. Here the power split between ES1 and ES2 is achieved in a smooth way (no switching) by fuzzy-rules and membership functions [26]. This strategy can be easily tuned to achieve nearly optimal operation. Rule-based energy management approaches can handle measurement imprecisions and component variations quite well.

The main feature of optimization-based approaches is the minimization of a cost function. Optimization-based approaches can be distinguished into global (off-line) and real-time (on-line) algorithms. Frequency decoupling is well suited for real-time applications. It is usually accomplished by a simple low-pass filter or by advanced filter concepts based on wavelet or Fourier transform. The low frequency component supplies the set-point value of the power controller of ES2, the high frequency component is covered by ES1 [27]. Another promising and widely used optimization-based energy management approach is the equivalent fuel consumption minimization strategy

(ECMS). It is aiming for the minimization of an instantaneous cost-function (e.g. efficiency or H_2-fuel consumption) [28]. Other energy management approaches are based on classical PI-controllers [29] not requiring expert knowledge and allowing to be tuned easily on the basis of an on-line adaptation law.

At Chemnitz University of Technology different energy management concepts for HESS are being developed, investigated and experimentally tested, including a rule-based approach [30], an approach based on dynamic programming [31] and a combined control- and optimization-based, hierarchical energy management [32], [33], [34], which is illustrated in Fig.3 for the example of a fuel cell-direct storage-HESS. This algorithm divides the control and optimization problem into three layers: the primary control of bus voltage and fuel cell current, the secondary control to limit fuel cell operating range and power gradient and to perform battery charge and load-following control, and the system control to optimally adjust the secondary control parameters aiming for the minimization of H_2-consumption and dynamic fuel cell stress parameters.

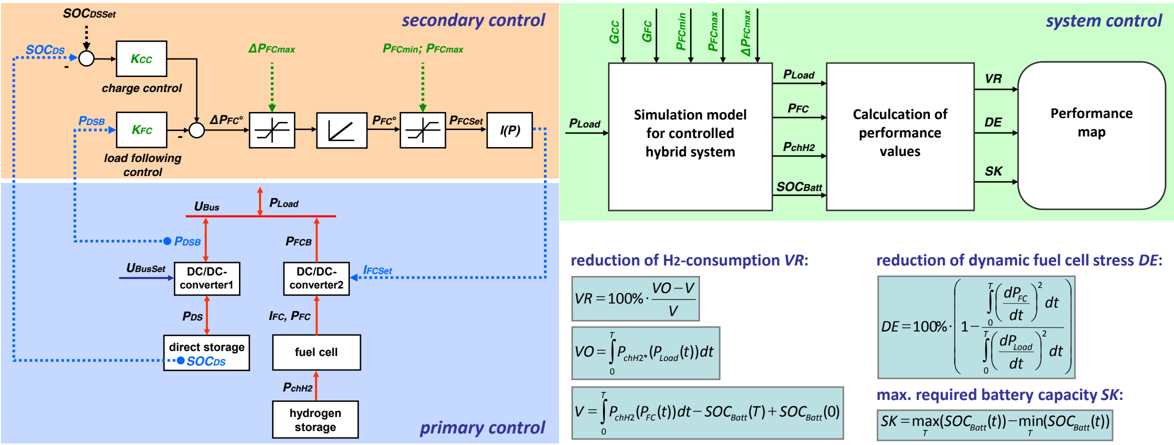

Fig. 3.Hierarchical energy management: primary level (voltage and current control), secondary level (SOC-/load following control) and system level (global optimization) [33].

HESS design/sizing and energy management optimization problems are usually strongly interdependent. Therefore, intelligent HESS-design algorithms take into account both, component sizes and energy management parameters. A particle-swarm optimization algorithm was successfully employed demonstrating good convergence, fast computation speed and an excellent handling of the complex, non-linear optimization problem [35].

3. HESS for renewable energy applications

3.1. Principle of power flow decomposition

Fig.4 presents a PV-HESS-example and demonstrates in a simplified manner the decomposition of the difference power ΔP (PV minus load power) for a 5kW PV-plant and a four-people household (with 4MWh/a energy consumption) at a reference site in Chemnitz.The first step is the peak shaving (power-to-heat conversion) for ΔP values greater than the threshold value ΔP_{PS}. The remaining power is low-pass filtered with filter time T_{F1} leading to the long-term trend component ΔP_{F1}. The remaining power ΔP_{R1} is filtered with filter time T_{F2} leading to the daily trend component ΔP_{F2}. The residual power ΔP_{R2} contains the remaining fast power fluctuations and part of the peak power. Fig.4e) shows the histogram of ΔP indicating that a significant peak shaving can be realised by converting only a small amount of PV-energy into heat (orange area). Fig.4f)-h) illustrate the cumulated power of ΔP_{F1}, ΔP_{F2} and ΔP_{R2}, corresponding to the state of charge of a virtual long-, mid- and short-term energy storage (a rough estimation of the required storage capacities gives about 1000kWh, 10kWh and 200Wh).

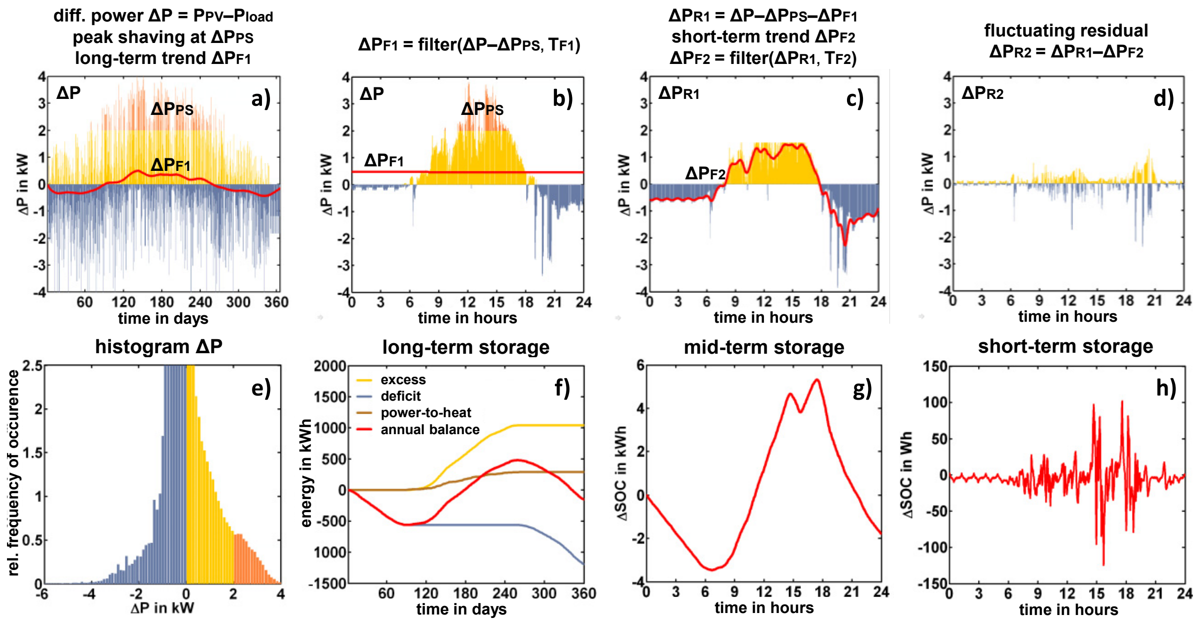

Fig. 4.Example of the power flow decomposition for PV-HESS-application.

3.2. HESS-configurations for PV-applications

Fig.5a)-d) illustrate four HESS-configurations, which can be beneficially employed in the context of decentralized PV-systems.

Fig.5a) shows a combination of a power-to-heat unit and a battery. This HESS-configuration can be used for advanced self-consumption optimization integrating a PV-peak shaving functionality and hereby achieving a significant stress reduction and increase of battery lifetime. Additionally, this HESS-configuration can be used for generation and storage of hot water from excessive PV-energy or electricity from the grid at times of low tariffs.

Fig.5b) shows an HESS-configuration similar to the previous one with an additional H_2-storage path [17], [38]. Due to the battery, this configuration offers great potentials for the optimization of electrolyser and fuel cell efficiency and lifetime by limitation of operating ranges, number of on-/off-switching and prevention of power gradients and dynamic stress. In this HESS-configuration electrolyser and fuel cell only have to cover the maximum of the long-term trend ΔP_{F1} (s.Fig.4). The nominal electrolyser and fuel cell power can be significantly reduced (compared to a power supply without battery) and can be independently chosen from the capacity of the H_2-storage tank. Both measures can lead to significant cost reductions. Moreover, the conversion heat of electrolyser and fuel cell can be utilized leading to high overall system efficiency (electricity and heat). The HESS-configuration of Fig.5 can be applied for sustainable, zero-emission on- and off-grid applications with different possibilities to place the H_2- and heat storage-path (e.g. building integrated, or centralized on a district or community level, possibly with access to a local heat and/or gas network). The efficiency and lifetime-optimizing energy management algorithm for this HESS-configuration can adapted to larger power-to-gas applications.

Fig.5c) shows a HESS-configuration to cover the short- and mid-term range. The supercap here functions as the “high-power” storage, covers peaks, transients and fast power fluctuations. This helps to avoid battery stress (e.g. high charging currents and micro-charging cycles for a lead-acid battery) and as a consequence increases battery lifetime.

Fig.5d) shows a similar HESS-configuration only with a “high-power” battery (e.g. lithium-ion or lithium-titanate battery) instead of the supercap. In this case the “high-energy” storage could e.g. be a cheap lead-acid battery (with interesting, supplementary charging/discharging-, SOC- and operating characteristics to the lithium-ion battery). Instead of the lead-acid battery also a redox-flow or a high temperature battery could be utilized to cover the mid-term power fluctuations. The resulting “hybrid battery” can be beneficial for many renewable energy applications. The configuration requires intelligent charge control (for both batteries) and energy management strategies capable of precise modeling of battery state of charge, state of health and the estimation of the influence of different operating regimes onto the battery lifetime.

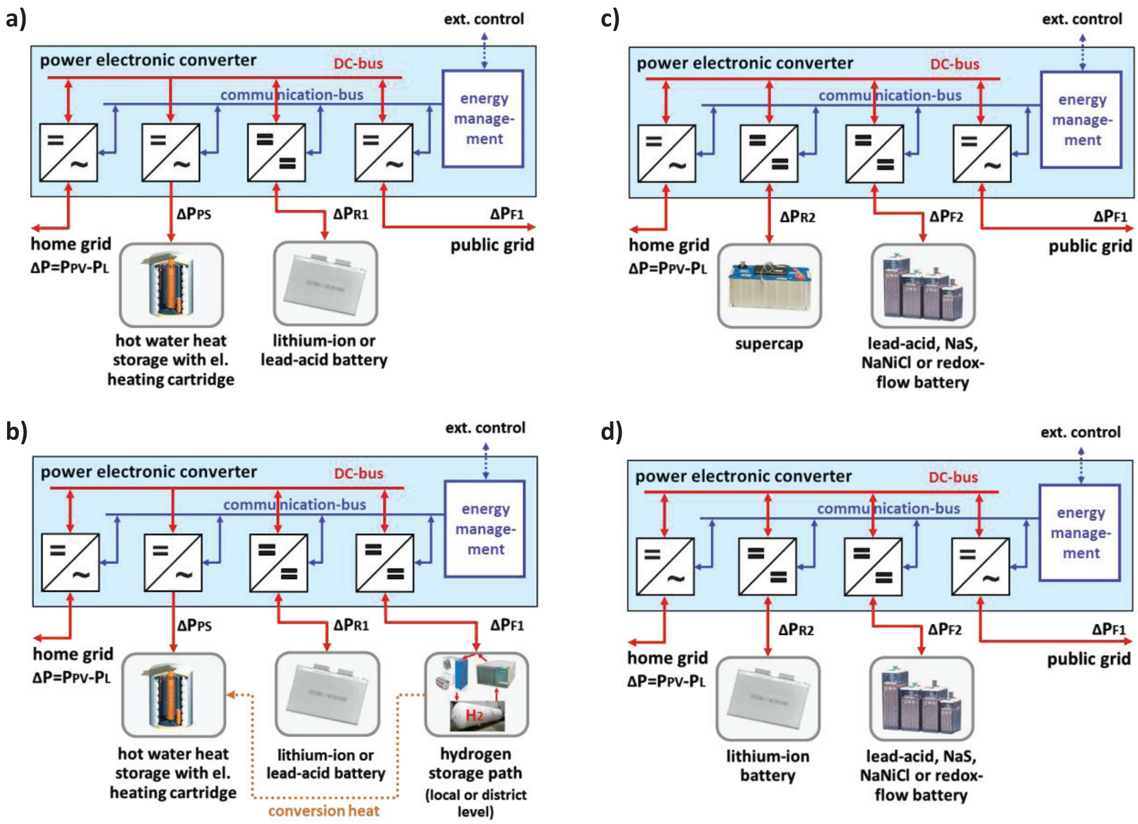

Fig. 5.HESS-configurations for the application in decentralized PV-systems.

3.3. HESS-experimental test-bed at Chemnitz University of Technology

Fig.6 shows part of the HESS-experimental test-bed at Chemnitz University of technology. It is used for experimental investigation and testing of control and energy management algorithms for various types of HESS-configurations and different applications [30].

Key component is the modular power converter system, which consists of up to eight bidirectional DC/DC- and DC/AC-converters with a nominal power of 2.5kW and various voltage ranges on the input/component side (0-45V, 0-60V, 0-230V). The converters are coupled via a common 400V DC-bus. The converter system incorporates a novel power flow control concept, which is characterized by inner current control loops and outer voltage control, which can either participate in the control of the bus voltage or the control of the voltage at the component side [36], [37].All controller parameters and set point values can be software programmed and adjusted from the Matlab/Simulink control environment. Here also the emulation of dynamic PV-supply and electricity demand profiles, as well as “virtual components” via programmable power supplies and loads is realized.

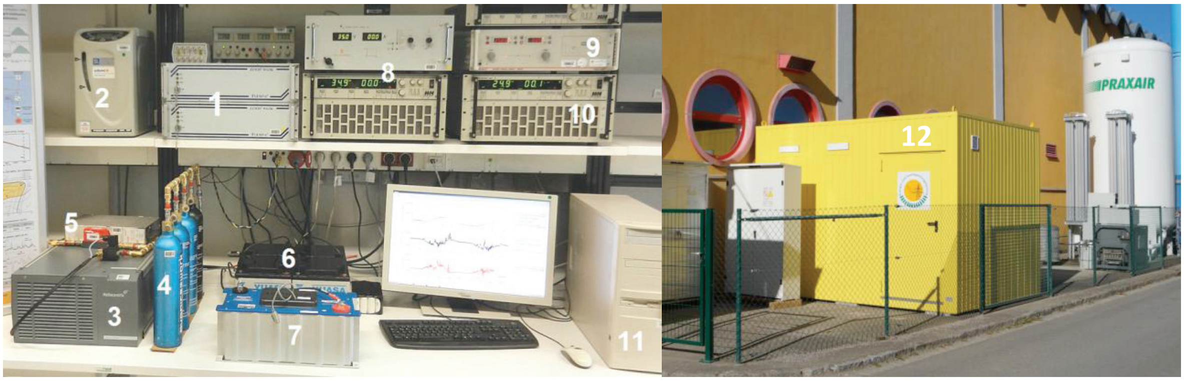

Fig. 6.HESS-experimental test-bed, 1: power converter system, 2: PEM-electrolyser, 3: PEM-fuel cell, 4: H_2-metal hydride storage tanks, 5: fuel cell DC/DC-converter, 6: lithium-ion and lead acid batteries, 7: supercap, 8: virtual battery, 9: virtual fuel cell, 10: virtual electrolyser, 11: energy management PC with Matlab/Simulink control and monitoring software, 12: H_2-storage path.

4. Summary and conclusion

HESS are an interesting and very promising flexibility technology, which can help to cover short-, mid- and long-term fluctuations in a future sustainable, 100%-renewable energy system. This paper has given a short overview of typical HESS-applications, energy storage coupling architectures, basic energy management concepts and a principle approach for the power flow decomposition based on peak shaving and double low-pass filtering. Moreover, four HESS-configurations, suitable for the application in decentralized PV-systems, have been briefly discussed. Current research at Chemnitz University of Technology is focusing on the development, investigation and experimental testing of new control- and optimization-based energy management algorithms and optimizing design concepts for HESS.

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