Storage Technologies for Charging Infrastructure

Variant Analysis and Methods for Storage System Assessment

René Unger, Monika Wicke
EA Systems Dresden GmbH
Dresden, Germany
rene.unger@ea-energie.de

Claudia Hain
NACOMPEX GmbH
Bad Saarow, Germany
claudia.hain@nacompex.de

***Abstract* — in high power vehicle charging applications, local electric storage systems will have significant impact on infrastructure cost and grid stability. Sufficient local storage capacities are required for using a significant amount of renewable energy as well.**

In this paper a possible interstate charging scenario with local renewable energy is shown. Based on estimated demand, charging load curves are generated. In a whole system simulation with other local electricity and heat consumers the characteristics of a suitable storage are evaluated. These characteristics are then matched to available and future storage technologies and their integrational concepts.

This paper shows a toolset and layout evaluation method for such strategic infrastructure decisions like storage size, technology and energy system integration.

Keywords: storage technologies, charging infrastructure, load profiles, systems simulation

I. INTRODUCTION

For the coming years, almost all big car manufactures have pronounced electrical vehicles with a range from 300 to 500 km. Many business models incorporating these vehicles are based on a short charging time of less than an hour. In the future, the rapid development of vehicle batteries will allow high charging power which will be a huge challenge for the electrical distribution grids as well as charging infrastructure.

A simple example for demonstration: To charge a realistic range of 500 km (100 kWh) within 30 minutes, an electrical power rating of 200 kW is needed – for one vehicle. For comparison, the power ration of a medium sized production enterprise is between 250 and 1500 kW. Charging vehicles of this power class at home like shown in [5] is often not viable. Therefore this paper examines centralized charging options at a common interstate fuel station.

The high peak load requirements correlate well to the current challenges in the energy transition. Integration of dynamic renewable source like wind or solar power, stability and security of supply, cost mitigation for grid expansion as well as peak load reduction for charging infrastructure are major issues.

Decentralized peak load buffers are an option to couple the formerly separated sectors of energy and transportation as well as heat and electricity. Buffering of fluctuating local renewable energy for fast charging furthermore enables a real environmentally friendly mobility. It also helps to significantly reduce the power peak which will be much higher than current daily peak in the nationwide grid if a high ratio of vehicles will be electrified (2030+).

To evaluate the feasibility of different settings and storage technologies, new simulation methods and libraries were developed. These are based on modern libraries for energy

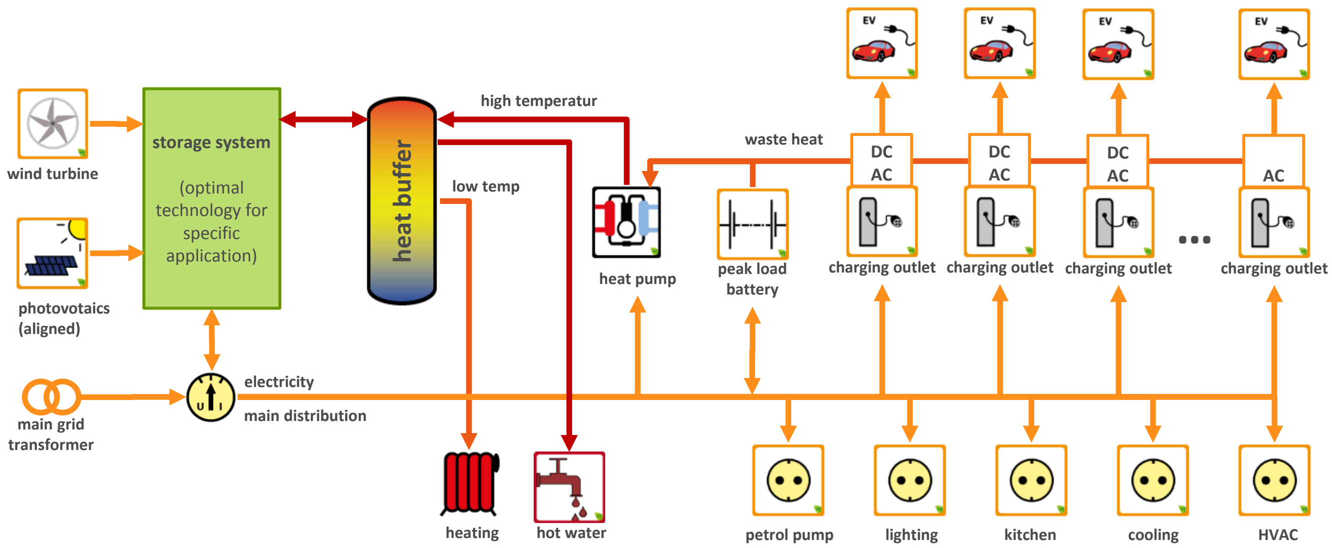

Fig. 1. System concept for renewable fueling and charging station

system simulation in Modelica, the Green Building and Green City Libraries of the SimulationX platform.

The Simulation is integrated into a preprocessing toolchain for statistically built mass charging profiles, building load profiles. The final parts of the toolchain are processing algorithms to calculate characteristic values for the selection of optimal storage technologies and component sizing. To demonstrate the toolchain an exemplary setting is described in the following section.

II. The Fuel Station Setting

The postulated interstate fueling and charging station offers:

- 12 DC charging outlets @ 100 kW each,
- 6 AC outlets @ 22 kW,
- 70 truck parking lots with sanitary tract and showers,
- Food court (kitchen, cooling chambers).

Renewable energy is provided by a

- 1200 kW wind power plant (100m hub height) and
- 160 kWp alignment controlled photovoltaic generators.

A storage system is installed. The required capacity and power characteristics were measured from the simulation results.

a) direct charging scenario

All renewable energy is fed directly to the storage first. The storage is used to buffer power peaks from and to the grid. For example if wind power is directly transmitted to air compressors.

b) gridparallel scenario

The storage is parallel to the main grid distributor. This increased possible transformer losses but has potential to decrease power requirements and system complexity.

The dissipated low temperature heat of charging transformers as well as of the storage is used as major source for heating via heat pump. This way, room heating and hot water is provided with high efficiency.

Additional consumers like parking space lighting and fuel feeder pumps etc. are part of the simulation too.

The local supply system consists of a medium voltage main distribution which connects area grid, storage, charging grid wind power and transformer for 230V low voltage main distribution. In low voltage there are lighting, heat pump, kitchen, auxiliary pumps and smaller consumers.

The station is situated near Dresden but locations like Berlin Schönefeld or Leipzig Hermsdorf would generate similar mobility profiles and timetables consisting of commuters and some long distance trips.

III. Requirements - Future Charging Load Profiles

The analyzed charging load profiles were generated based on three main groups: commuters, intercity business traffic and leisure trips during evening hours and weekends.

Inputs for the new charging job generator tool were:

- Timetables with vehicle arrivals and state of charge based on mobility studies like [1]
- Vehicle type descriptions, charging power curves for vehicles with 50 and 100 kW maximum charging power
- vehicle registration distribution based on estimations for post 2020
- A behavior model for selection of charging method and duration (breakfast, full charge, etc.)

An exemplary weekly schedule is shown in figure 2.

By using reproducible random numbers, lists of charging jobs for low, medium and high traffic load were calculated, each with arrival times, remaining charge / distance, expected duration of stay, and other strategy influencing factors.

For example one high traffic scenario had about 59,000 charging jobs in a year with a total energy of app. 1,600 MWh or 1,725 MWh including inverter losses.

This multi-agent-algorithm then distributes the requests to the available charging outlets. This way the peak utilization on Monday mornings led to a worst case waiting queue of four. As expected AC charging was almost never used with the respective agents deciding to postpone charging or waiting for an available DC outlet.

During other weekdays the peaks are lower. For the testing scenario there is higher traffic on Friday, Saturday and Sunday evenings, generating loads when less renewable energy is available.

Vehicles Arriving

time (veh/h)	Mon	Tue	Wed	Thu	Fri	Sat	Sun
...							
2:00	0	0	0	0	0	0	1
3:00	0	0	0	0	0	0	0
4:00	0	0	0	0	0	2	1
5:00	5	5	5	5	5	2	0
6:00	16	9	9	9	9	2	2
7:00	18	13	13	13	13	5	5
8:00	22	15	15	15	15	9	9
9:00	17	13	13	13	13	11	11
10:00	9	9	9	9	9	15	15
...							

Fig. 2. Typical arrival schedule for charging requests (higher loads)

The following chart shows the utilization of outlets and the combined peak power for the worst case scenario.

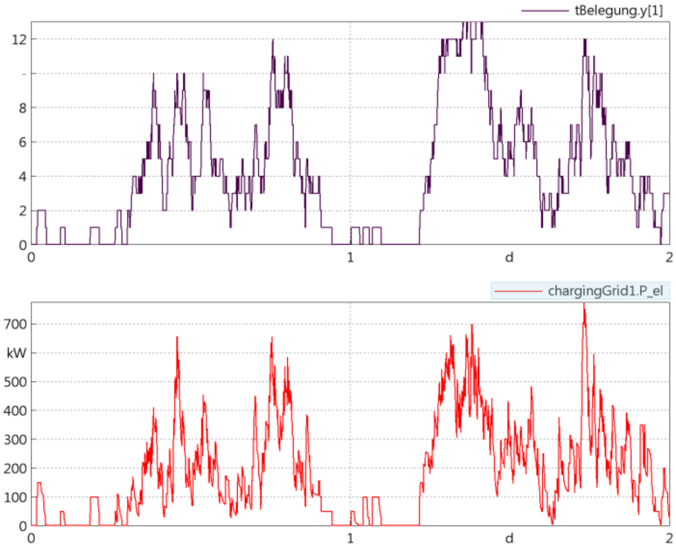

Fig. 3. Number of used outlets (top) and total charging power (bottom) for Sunday and Monday (right)

IV. TOOLSET AND SIMULATION PLATTFORM

For calculation the SimulationX platform was used. The models are built in Modelica, a non-causal language for multi-physical and control systems.

An overview of the model is shown in figure 10. Each block consists of various subcomponents integrating system physics, usage profiles and control strategies. Also all major losses were modelled. Many of the models like building, heat pump heating system, wind turbine and photovoltaics were used from the Green Building and Green City Libraries, specialized in such energy system simulations.

For the charging grid, performance and the use of preprocessed curves were essential. The library models like charging station and battery electric vehicles with detailed cell and inverter characteristics, even aging were much too detailed for the simulation task of 50,000+ charging jobs. Therefore new models for universal outlets and a charging grid for use with the preprocessed curves from multi-agent-simulation were used (Fig. 4).

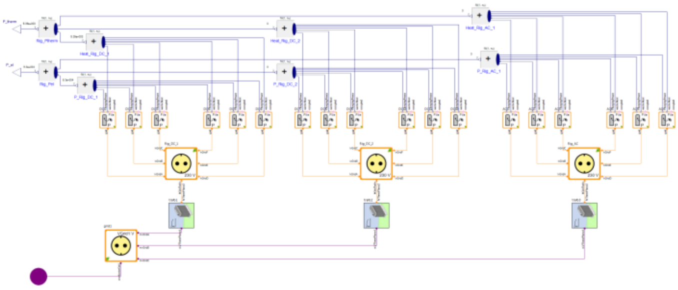

Fig. 4. Model of the charging grid with 12 DC and 6 AC outlets for coupling with charging job preprocessor

Common storage models like batteries could not be used because the characteristics of the system were not known but object of study. Therefore a universal electrical and heat storage model was developed. With this it is possible to simulate technology tolerant the transfer of electrical and thermal power from and to the storage system as well as efficiencies and internal conversion between both. The storage fulfills every demand of the controlling algorithm. So in post processing capacity and power characteristics could be read from the simulation data and fed back to the parameters of the storage controller for the next run.

Simulating a year currently takes 1-5 hours (i7, 2.7 GHz) depending on how sophisticated the control algorithm is. For a more detailed view on control strategies (model predictive control, dynamic optimization, etc.) statistically correct scenario analysis as described in [2] can be used.

V. FIRST RESULTS

The two scenarios: direct and grid parallel charging were

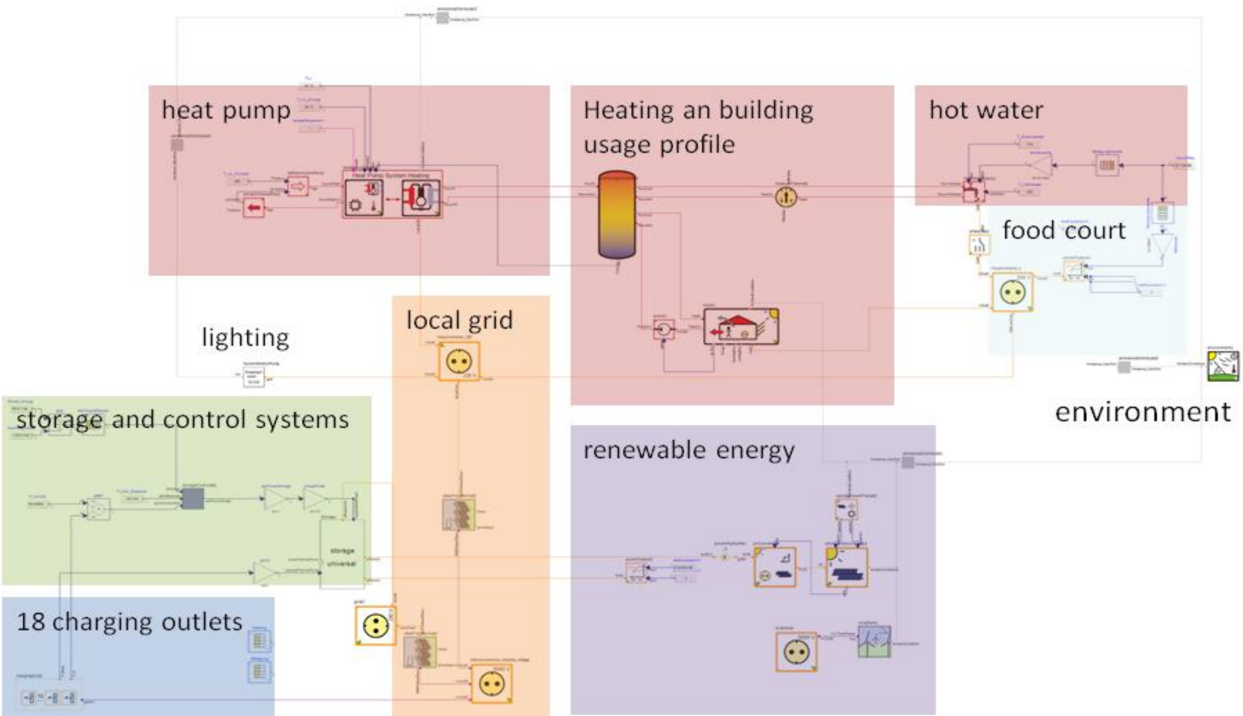

Fig. 10 - Overview of simulation model

evaluated for medium and high traffic. System layout and component sizes were defined analyzing variants in short term (week) simulations. Later storage size, control curve and wind power generator were matched to fit the high traffic scenario. Then, the completed models were run in the yearly simulation.

A. Size of Storage

To compensate for charging power peaks, 1 MWh storage capacity would suffice for most weather conditions. Yet in some scenarios, even with a large storage of 4 MWh and a lot of installed surplus wind power, the storage gets empty. These result in higher load peaks than desired. Thus for effective peak load reduction the storage needs recharging from grid.

On the other hand, windy days generate much more energy than needed. Capturing this entire surplus without exceeding a transformer limit of 300 kW would require a storage capacity of more than 10 MWh (see fig. 5). Since wind power peaks will likely occur when the national grid is saturated with wind power anyway, complete wind energy storage should not be a design rule.

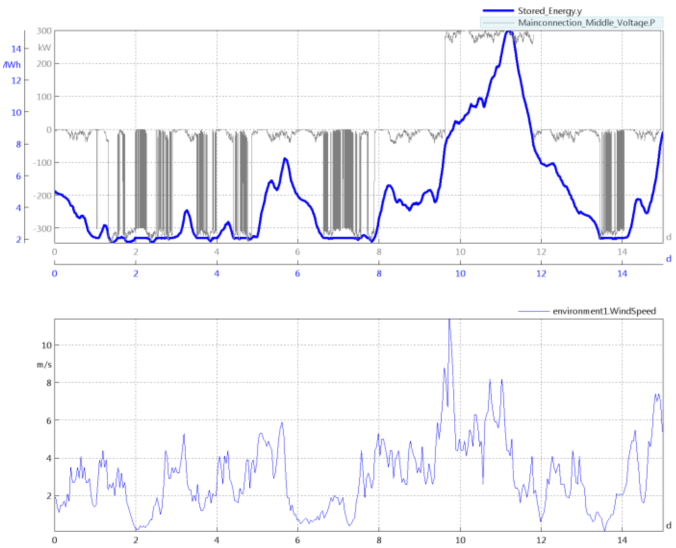

Fig. 5. Example with 10 MWh storage showing windspeed (bottom) and overshoot in storage state of charge vs. 300 kW transformer limit

A suitable first layout for both scenarios was 2 MWh of storage capacity with a simple control strategy:

- Recharging from grid when state of charge (SoC) was less than 50%
- Discharging to the grid when SoC was higher than 80%

This was enough to buffer the Monday morning peaks and still have enough surplus capacity for storing most of the needed renewable energy.

B. Power Requirements

The maximum discharge power was defined by the total power demand of all charging outlets and electrical consumers. Major impact had the charging outlets.

The worst case scenario with all consumers at maximum and no renewables would be up to 1400 kW at the main grid connection. Therefore the major storage strategy was to limit the grid connection to 300 kW but adjust to zero when possible.

The grid parallel scenario had the lower and more even distribution but still reached totals of 1 MW with a long term effective value of app. 400 kW for storage discharge power.

By a more sophisticated strategy using prediction to limit storage power too, this can be reduced to app. 750 kW which would significantly reduce system cost.

Of cause these numbers would change with different traffic scenarios and vehicle mix.

The maximum charge power was defined by a sunny and windy day with app. 1200 kW total renewable power. This was mitigated to about 1000 kW by the demand of vehicles at outlets.

The statistical simulations confirmed also the first assumptions concerning the rate of power change. The worst case was the arrival of two vehicles at the same time and resulted in a 138kW/minute change. Given future navigational systems and automatic reservation of charging outlets this will be enough time to start up all of the possible storage processes.

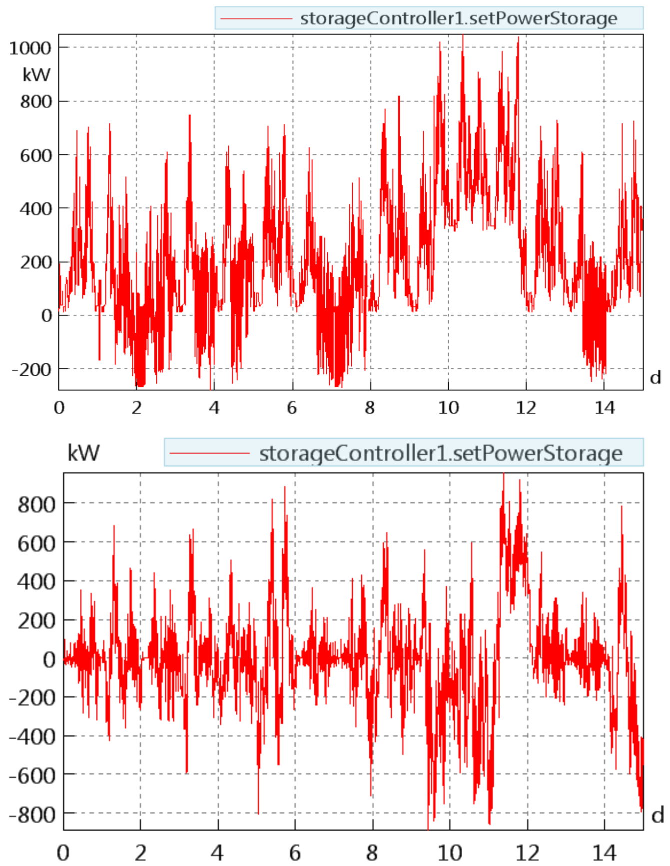

Fig. 6. Power curve for the 10 MWh storage showing high power peaks; direct charging scenario (top) and gridparallel storage (bottom)

C. Energy Balance

To demonstrate the rough energy distribution, all major energy suppliers and consumers are shown in the following figure. Due to the nature of business processes and the underlying vehicle technology, there are even more assumptions than the system characteristics before.

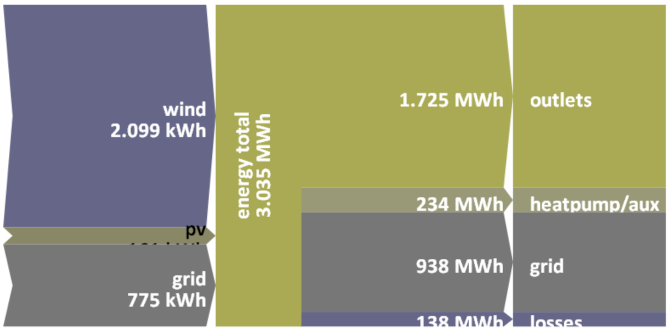

Fig. 7. Electrical energy balance for grid parallel scenario (2MWh capacity, 1MW power, 300kW peak)

VI. Storage Technologies

The simulation results will be used to basically evaluate the following technologies for use in the described charging scenario:

- Solid state batteries: Container type industrial storage system with Li-ION cells
- Adiabatic pressurized air storage
- NaCompEx® NaOH storage plant [4]
- Future Metal-Metaloxide-Storage (MeMox) [3]

A. *Large Battery electrical storages*

Suitable systems are available in capacities from 5 kWh to 10 MWh. Industrial applications usually use Battery Packs combined in 19” Racks. These Racks are installed together with power electronics and cooling systems. A 40 ft. ISO-Container with state of the art technology holds approximately 1 MWh with 1 MW peak power.

Main cost drivers are the cells. Costs are scaling linearly with capacity. Power electronics together with cooling systems are scaling almost linearly with peak power. Total costs for current installations range from 500-1000 €/kWh almost independently of the size of the battery.

There is good potential for halving these costs in the next 10 years. Warranties for stationary batteries have grown to more than 10 years and more than 10.000 cycles. Single Racks can be serviced easily for long term maintenance beyond that. Therefore storage costs of less than 50 € / MWh seem realistic.

From system engineering view, the advantages of batteries are good scalability for power and capacity, fast response to power demand [<1s] and easy maintenance. Disadvantages are the high initial and running costs as well as the need for rare materials in cells and power electronics.

B. *Adiabatic Pressurized Air Storage*

Compressing air for storage and expanding it when energy is needed is a technically simple process. The difficulties are in efficiency. For process efficiency, the heat recuperation is essential, but technically most challenging.

Major cost drivers are the turbines for compression and expansion as well as the auxiliary systems. The costs for storage volume depend on system pressure.

High efficiency and storage density require higher system pressure. Because pressure vessels are expensive, capacity restraints are similar to those of batteries.

While installation costs are high, operational costs for storage are low, basically defined by thermal losses and maintenance. The lifecycle of such installation in industrial applications is measured in decades rather than years. Considering storage capacity cost this technology is best suited for peak buffering and high cyclization.

From system engineering view, this storage uses common industrial technologies and has a long lifetime. Useful is also the possibility to generate cooling power in the expansion stage. On the downside is difficult scalability for part-load-applications. For storage plants there exists an economical minimum size in power and capacity. Additionally the required installation space is much larger compared to batteries.

C. *NaCompEx® storage plant*

The NaCompEx® process uses different concentrations of sodium hydroxide solutions as hybrid storage for heat and electricity. The chemical basics for the underlying absorption and desorption process date back to the end of 19^{th} century. The technology can be implemented using components and technology proven in power plant and chemical industry.

Major cost drivers are the storage and recuperation components while storage volume costs are even less than for compressed air storage. Volumetric density is adequate as well containing 60 kWh/m³ of electricity or 350 kWh/m³ of heat [4].

Advantageous for systems engineering is the capability to use waste heat to improve storage efficiency to about 80% which is much better than air storages in first place. The heat integration also allows coupling to nearby biomass facilities (waste heat) as well as to heat consumers like hot water demand of the sanitary tracts of the fuel station.

Disadvantage is the technological complexity of the process which makes it better suited for larger storage solution. This technology would be ideal in combination with a nearby wind park or industrial site.

D. *Metal-Metaloxide (MeMox) Storages*

Highest chemical storage densities can be achieved using the oxidation of metals as described in [3]. The energy is stored in the different oxidation levels of metal (i.e. iron). The storage process using iron was described in detail already 1976 in [6] and put into industrial application shortly after.

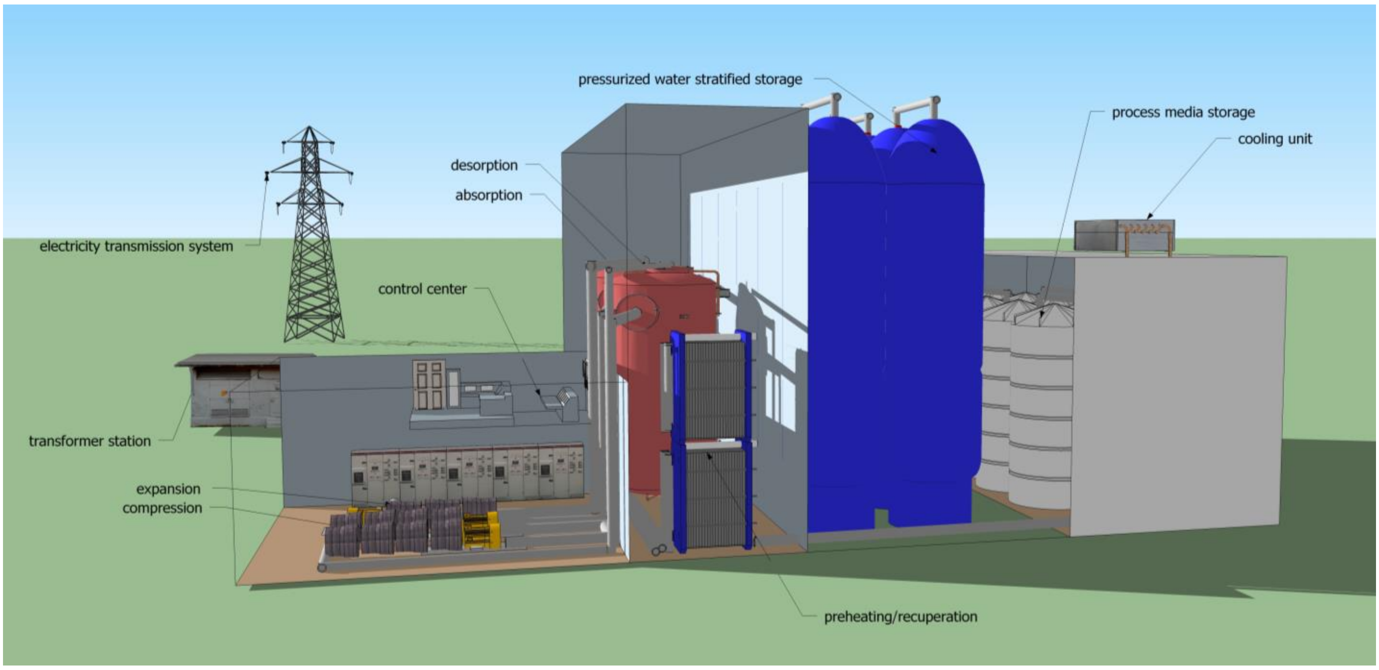

Fig. 11 Overview NaCompEx® storage plant

For charging, standard pressure hydrogen is pumped into the heated metal composite reducing the oxides to plain metal. The returning hot water vapor is separated to oxygen and hydrogen in steam electrolysis.

For discharging, the process is inverted; using water vapor to oxidize the metal, the returning hydrogen can be converted to electricity using fuel cell technology.

This concept still requires a lot of technological research. Especially important is materials science for the metal-ceramic-composites to ensure high cycle times and long term stability.

Components like steam electrolysis (SOEC) are currently reaching industrial readiness [7]. Other surrounding machinery is state of the art and much simpler and smaller than that needed for compressed air i.e. because system pressure and mechanical requirements are low.

The possibilities for a future electricity and hydrogen based infrastructure are extraordinary since MeMox as a circular process:

- combines electricity, heat and hydrogen storage within the same process
- storage materials are environmentally friendly and are inert most of the time (hydrogen bound to metal)
- storage capacity is very high (between batteries and fossil fuel)
- storage material (i.e. iron ore is inexpensive)

Major cost drivers for this type of storage are the fuel cells to extract electricity while storage capacity is inexpensive and of very high volumetric density.

The possibility of MeMox to store and generate of hydrogen locally is highly interesting for fuel cell vehicles and future generations of range extenders.

The possible energy density is about one third compared to diesel fuel. An electrical drivetrain is much more efficient and has better torque characteristics compared to a combustion engine. Therefore in the long term future, the process could also be used for heavy duty vehicles and trucks as well.

VII. Specific Conclusions

The simulation shows that the considered fuel station setting is primarily electricity-driven while building heating and hot water can almost be neglected. Even the large truck parking lot does not generate enough hot water demand to have significant impact.

While a storage capacity of 1 MWh seems to be sufficient buffer for the considered charging scenarios. It is not enough to balance renewable generation. 2 MWh increase renewable percentage significantly. Higher capacities still increase renewable share but even 10 MWh won't be enough to go 100% renewable.

With suitable predictive control algorithms, the charging and discharging power of the storage can be much lower than the worst case demand (60%), without postponing charging jobs or violating grid transformer limits. Essential part of the control algorithms will be low and part load efficiency as well as the proper handling of minimum power requirements

The proposed storage requirements can be fulfilled by current industrial scale LiIon-batteries technology. Still this is not a good solution. The simulations have shown that capacity is much more important than power. Modern battery technologies like lithium titanium provide extremely high power but are cost intensive for capacity.

VIII. GENERAL CONCLUSIONS

New technologies like NaCompEx® storage plants or the Metal-Metaloxide (MeMox) process are more expensive regarding power but have low costs for storage capacity.

For strategic long term solutions MeMox offer high energy density at low cost and a lot of synergies to other systems. Especially the ability to store and generate hydrogen locally is perfectly suited to charge fuel cell vehicles and fuel cell range extenders.

Comparing the technical parameters to a truck diesel engine in size, weight and price, small MeMox storages could replace the conventional drive train. This provides a realistic possibility (energy density) to fuel future heavy duty vehicles with renewable energy.

Of economic importance is the comparatively small average load of the investigated storage system layout. The reserves can be used for other grid convenient services like day-night-shifting, grid stability and phase symmetry as well as emergency backup.

Summarizing, future fuel stations will become important centers in a renewable energy society providing fuels and electricity as well as grid stability and energy storage services. Since even fast charging will take some time customers need to be offered even more short term services (food, shopping or laptop spaces).

IX. OUTLOOK AND FUTURE WORK

This paper gives a first glimpse on the toolchain for fleet charging profile generation, storage system layout and development of power management algorithms. This will help to evaluate the oncoming technical challenges of charging infrastructure integration better.

Future work will integrate real dynamic load management algorithms using online multi-agent co-simulation. This will also enable testing of more sophisticated control strategies like model predictive control and machine learning and market price control.

Additionally, more detailed analysis on specific storage configurations will be carried out, especially of the hybrid storage combinations battery / NACOMPEX and battery / MeMox. With these, economic and ecological aspects regarding grid services will be a major subject of the oncoming research.

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