Thermoelectric district supply concept including e-mobility

A Mack\textsuperscript{1}, L Lackovic\textsuperscript{1}, W Lisin\textsuperscript{1}, C Blatt\textsuperscript{1} and H Garrecht\textsuperscript{1}

\textsuperscript{1}Department of Materials and Construction, Institute of Construction Materials, University of Stuttgart, Pfaffenwaldring 4, 70569 Stuttgart, Germany

Luka.Lackovic@iwb.uni-stuttgart.de

Abstract. The main objective of the environmental protection is the sustainable energy supply of residential areas. This is made possible by networking several buildings in the same district in order to produce a sustainable, efficient and self-sufficient supply of electrical and thermal energy. The second elementary topic is the conversion from combustion engines to electric mobility, i.e. from thermal to electrical energy. A novel concept of networking different storage facilities, energy producers and consumers will enable a sustainable, self-sufficient energy supply for districts. A special feature of this energy management design is networking of electrical and thermal systems with subsequent integration of electro-mobility into the districts plant system. Energy consumption and energy generation were simulated in an exemplary project of a district containing three new low-energy buildings. The results show that a self-sufficient supply of this district is possible with intelligent control of charging cycles and charging capacity and with the use of a new storage facility for electrical energy - a Compressed Air Energy Storage system. This model concept makes not only a considerable contribution to the electro-mobility conversion, but also enables an energy-efficient and sustainable electrical and thermal supply of the district.

1. Introduction

Sustainability and environmental protection are two elementary objectives of modern society. In order to achieve an energy-efficient and self-sufficient energy supply for districts, intensive networking of the individual buildings and control of the various components is implied. For this purpose, a concept based on networking and self-sufficiency was developed on the Institute for Materials in Civil Engineering at the University of Stuttgart. It combines thermal and electrical subsystems of plant engineering equipped with a Compressed-Air Energy Storage (CAES) technology. As the politics in the automotive industry currently show a descending trend toward the CO\textsubscript{2} emission reduction, a further goal would be therefore to switch to integrated electro-mobility concept in the residential sector. This is only efficient and sustainable if the required power would be generated from renewable sources. The present concept integrates electro-mobility into the system scheme and serves as a modular, universally applicable approach for the energetic supply to district typologies of different sizes. It is based on intelligent planning through simulation, networking and control of different generators, storage facilities and consumers.

The developed district networking concept is based on an intelligent distribution and the temporal shift of the generated power by means of electrical and thermal storage. It is designed under three main assumptions: (I) the parking spaces in the district are designed as electric vehicle (EV) parking spaces, (II) the self-sufficient energy supply of these parking spaces is made possible through electrical energy
storage and (III) the energy is obtained from the photovoltaic elements of hybrid photovoltaic thermal collectors (HPTC) or the CHP unit (Combined Heat and Power). This superposition of the generated and required energy curves is made possible by Compressed Air Energy Storage, as it is depicted in figure 1. The function of this mechanical energy storage system is explained in detail in section two. In order to achieve a self-sufficient energy supply for the electric mobility, intelligent regulation of charging cycles and charging capacities is absolutely necessary. The control concept for the charging and discharging scheme of the EVs is explained in detail in Section three. Further on, additional challenge would be increasing the supply of the energy produced by renewable sources to the residential district. In the following, the individual components as well as their networking and interactions are described, where the individual residential buildings are designed as multi-family houses with low energy standards.

Residential areas usually have different energy requirements which take into account the electrical base load, consisting of lighting systems for outdoor areas and apartments as well as electrical appliances. In addition, there is a thermal base load due to the hot water consumption implying a high temperature requirement and, considering the fact that the system will use an underfloor heating system, the thermal loads for heating purposes as a low temperature demand. Additionally, a special feature of this concept is the electrical demand for the electric vehicle charging stations in the garage.

![Figure 1. Symbiotic energy supply concept.](image)

The photovoltaic system and the electrical part of combined heat and power generation serve as main sources of electrical energy supply. The CHP unit ensures a daily electricity generation covering the base load for appliances and the lighting system, while the hybrid photovoltaic thermal collector system intends to cover the demands of EV charging stations. The energy generated here can be stored mechanically by the CAES system and taken out in a phase-shifted manner. If, at the moment, the EV electricity demand is satisfied, the hybrid photovoltaic thermal collector system or the electrical storage directly covers the residents’ electricity demand. The CHP generation and thermal collector serve primarily to cover the high temperature demand. This energy is facilitated via a high-temperature network and used to provide hot water supply. If the buffer storage tank between the CHP unit or HPTC
and the consumer is fully loaded, the CHP unit or HPTC feed the heat energy into the latent heat storage tank. This energy storage is primarily charged with the energy from the heat pump, which is further supported by geothermal conic baskets. The baskets are placed in the ground where the water/glycol mixture is using higher soil temperatures in order to increase the COP of the heat pump, i.e. to reduce the evaporator power. The thermal energy from the heat pump or the latent heat storage tank is used to cover the heat demand. For this purpose, the heat is distributed by means of surface heating systems, which require a low temperature flow of 35°C and thus a low-temperature network. The result is a twonetwork distribution system. Due to the special properties of different components, further synergies are created which mutually benefit each other. Excess energy from photovoltaics can be used to run the heat pump in order to regenerate the soil. The Compressed Air Energy Storage can be integrated into the thermal system by using the waste heat generated in the compressor to fill the buffer storage or the latent heat storage tank. To discharge the storage tank, thermal energy is required as a catalyst to increase the temperature of the water in the tank, which is taken from the CHP unit.

2. Small scale hydro pneumatic energy storage (HyPES)
Near-Isothermal compressed air energy storage is a electricity storage concept that has advanced largely in the past 20 years [1]. In comparison to diabatic or adiabatic CAES systems, this technology has overcome some of the limitations such as the use of turbomachinery to compress air around 70 bar before storing it. The key to improved efficiency of the isothermal HyPES systems is the ability of the technology to compress and expand gas near-isothermally over a wide pressure range, namely from atmospheric pressure up to 200 bar. This large operating pressure range, along with the isothermal gas expansion, achieves a seven times reduction in storage cost and volume as compared to classical CAES in vessels.

![Diagram of an ideological isothermal CAES system](image)

Figure 2. Work principle of an iCAES system [2].

Figure 2 shows the basic principle of an ideological isothermal CAES system. Hydraulic pumps isothermally compress air at high rates that permit high pressure air to exchange heat with its surroundings [3]. During the expansion process, the gas is able to absorb heat from its surroundings thus making the system suitable to work in an environment which involves refrigeration machines, air conditioners and heat pumps. In this case, system would adopt a natural refrigerant which is environmentally benign [4, 5]. This paper focuses on a micro-CAES system for electrical energy storage and air cycle heating and cooling for HVAC in a building. It represents a solution which is, concerning the operational costs, plausible enough for implementation together with heat sources such as CHP systems and heat pumps. The modular and flexible design makes them suitable for a wide range of stationary applications and low operational and maintenance costs. There are two possibilities of using a small scale CAES as a trigeneration plant (heating, cooling and electricity generation). One, implementing the surroundings to heat up the gas in the compressor and the second which uses a heat supply for gas heating. While both approaches show excellent performances in the exergy analyses, the choice of the technology depends largely on the components in the system [4].
When comparing these two approaches, the system with the heat supply requires lower electrical input in the compressor for the same electrical output. In that case, however, the system needs to be equipped with a combustion chamber usually operated with gas and it can’t provide the cooling effect. For example, when comparing the two approaches with the same electrical output of 1 kWh and the overall electrical storage efficiency of the system without any external thermal input with 57%, the system without heat supply requires 1.77 kWh of electrical input and gives out 0.99 kWh of cooling energy (-6°C). The system with the heat supply under the same boundary conditions would require 0.66 kWh of electrical energy input and 1.22 kWh of thermal energy [6]. Basically, the idea of this paper is to implement the CAES with air-cycle heating and cooling processes which could be very effective for distributed power networks [3]. Currently, there are two noteworthy companies in the field of iCAES systems on the market. LightSail, a start-up company in California, which has proposed a storing concept that involves a water spray embedded into the compression chamber for cooling purposes and Enairy from Switzerland, whose storage technology is considered in the present paper.

3. Electro-mobility

The concept of the electro-mobility charging management system is based on the idea of integrating charging process into the overall scheme in such a way that the interaction of the individual loading stations in the district function optimally. Taking into account all relevant aspects such as the current state of charge of the car, type of the charging station or battery storage, the number of cars currently charging, the forecast of requirements and storage capacity on the basis of consumer behaviour data, the weather forecast of the different charging times and a limiting deployment plan, which could possibly be specified by the vehicle owner at the charging station, a target function can be evaluated that reflects the quality of the self-sufficiency of the entire district and thus exerts an optimal charging management.
This raises the question of the formulation of an optimal distribution problem. This would possibly have the canonical form for a quality measure $J \rightarrow \min$, with some constraints $\dot{x}(t)$ and a control function $u(t)$. The quality measure $J$ to be minimized would have to be determined in such a way that a controller $u: \mathbb{R} \rightarrow \mathbb{R}^m$ achieves the loading process with an objective of maximum self-sufficiency. A negotiation/control strategy must be agreed upon and defined, in the sense of which the target function is to be solved. This imposes an equilibrium demand, as it occurs, for example, in the allocation of telecommunications licenses. This is intended to answer the question which maxima the load management system should follow. In order to maintain the self-sufficiency quality, it would be necessary to check whether a sufficient time horizon is guaranteed and how favourable the weather forecast is, with regard to PV generation. Furthermore, the charging times of individual vehicles as well as the consumer behaviour of the vehicle owners are further degrees of freedom for the assignment of priority data concerning the start of charging and the actual charging period of individual vehicles. This is needed especially in the case of a limited amount of available energy in the battery storage.

![Figure 4. Principle of a loading management system.](image)

When modelling load management, one can first distinguish between three basic principles of power distribution. These are static, dynamic and timetable-based load management. In the static model, each charging station is assigned a fixed maximum power. Thus, each electric vehicle is allocated the same charging power, regardless of how much a single car actually needs. In order to ensure that the residential area is as energy self-sufficient as possible, the charging capacity provided should depend directly on the current consumption of the entire residential complex. Such a distribution of the charging power is a dynamic charging management. In timetable-based power distribution, the vehicle-specific attributes, such as more predefined charging schedules, the typical consumption of a car or predefined maximum charging times for a charging sequence were to be taken into account. Operational execution could take place via a process control system. This system has access to the charging columns and can adjust the power output quantity if necessary. In the figure 4, the principle of a loading management system is outlined. Depending on the system state, any restrictions and evaluation of the quality measure, a circuit matrix is set accordingly on the basis of a control command. Any number of control strategies can be
formulated, each of which, taken separately, are individual algorithms of the load management system. For example, a FIFO logic (First-In-First-Out) could configure the switching state in such a way that the charge distribution at the columns is oriented to the connection time. Static charge management could be expressed by the fact that the power consumption at each column is the same and only depends on the number of cars currently being loaded. It would also be conceivable to adjust the control stratagem using a neural network concept.

The concept presented here is a draft for the time being and is still waiting for its qualified processor. However, the formulated explanations give the contours of a problem that will become more topical in building and energy technology to the extent that the demand for energy self-sufficient district grows. The interweaving of components that have never previously functioned together or never required mathematical formalization defines the complexity of the problem. With regard to the upcoming challenges in terms of energy system transformation, however, such tasks will have to be mastered.

4. Simulation results
A simulation for one summer week has been performed in MATLAB. The thermal and electrical consumption curves had been previously calculated in IDA ICE software. Using the example of a summer week from 16.07.2018 to 22.04.2019, the functionality of the Thermo-electrical system was validated. Thermal management strategy of the system is shown on the figure 5. The heat demand curve, depicted as red line in the figure, has very low values as the simulation was performed for one summer week. In this case there is practically no need for the CHP unit to be in operational mode because the thermal demand is being covered from thermal storage and solar thermal panels alone. The over-produced thermal energy from solar thermal panels was stored in the thermal storage unit for later use, depicted with brown area in the graph.

Figure 5. Thermal energy management.

Since the CHP unit is seldom used during summer week, the system has very low or none of the electrical energy produced from the CHP, which can be observed in the figure 6. On the other hand, as the CHP uses gas fuel for operation, there’s no CO2 emissions coming from fuel combustion and the system is becoming more self-sufficient. The electricity demand is being covered exclusively with energy from PV panels or compressed air energy storage unit as outlined in figure 6. From the complete amount of the excessive energy produced by the PV panels which is stored in the CAES unit, a part of
it is used for covering the electricity demand (light blue area) and part for charging the electric vehicles, as shown in figure 7.

**Figure 6.** Electrical energy management.

The grey coloured areas in figure 7 depict the periods when the system doesn’t have sufficient energy in the CAES unit to cover the E-mobility demand and the vehicles have to be charged form another source, such as CHP or the electric grid. The simulation was run under the presumption that all electric vehicles are being charged at the same time for 8 hours, i.e. the worst case scenario. With a 3 kW power charging station, the time is an average of 8 hours for full charging considering several models. This time frame was assumed for the simulation. These simulations were performed only as an example of system energy management and therefore don’t represent the concept of E-mobility charging strategy, as previously explained.

**Figure 7.** Thermal storage state and electricity used for E-mobility.
5. Conclusion
On the basis of the results presented above, it can be seen that the concept does not function completely independently, especially in winter, but that considerable amounts of energy can be saved by coupling the electrical and thermal networks in conjunction with suitable storage facilities. More detailed simulations have to be carried out to determine the exact overlapping of the load curves. In addition, the control principle for the loading and unloading of electric mobility must be defined so that the electrical requirements can be adapted and precisely incorporated into the simulation.

References
[1] Energy Storage association: http://energystorage.org/energy-storage/technologies/isothermal-caes
[2] SustainX Inc., Seabrook, NH, USA
[3] Kim Y M, Lee J H, Kim S J and Favrat D 2012 Potential and Evolution of Compressed Air Energy Storage: Energy and Exergy Analyses Entropy 2012 14 1501-21
[4] Verschoor M J E 2001 Ed. Guidelines for the Application and Design of Air Cycle Systems for Heating, Ventilating and Air Conditioning in Buildings (The Netherlands: TNOMEP, Apeldoorn)
[5] Shengjun L, Zhenying Z and Lili T 2011 Thermodynamics analysis of the actual air cycle refrigeration system Syst. Eng. Proc. 1 112–6
[6] Foster A M, Brown T, Gigiel A J, Alford A and Evans J A 2011 Air cycle combined heating and cooling for the food industry Int. J. Refrig. 34 1296–304