Articles

Management of electricity and heating demand to match sustainable energy supply

This paper presents the Dual Demand Side Management (2DSM) concept as well as an implementation on a multi-energy co-simulation platform. 2DSM is a coordination approach to manage the energy demand on a city district level. The coordination strategy enables the balancing of volatile renewable electricity generation by exploiting the thermal flexibility provided by decentralized energy supply units coupled with storage systems. The investigation of a small city district of 34 houses shows the suitability and the potential of the 2DSM concept.

Keywords: demand side management, scheduling, renewable energies, mixed integer problem, co-simulation.

The transition of the German energy infrastructure towards sustainable and decentralized energy generation requires and already induced significant changes of the structure and the operation of the energy supply systems e.g. the impending nuclear power plant phase-out and the ambitious goals for CO_2 emission reduction and expansion of renewable energy sources (RESs). This energy reform, widely known as the 'Energiewende', is based on several national laws mainly the German Renewable Energy Act (EEG), the Renewable Energies Heat Act (EEWärmeG) and the Act on Combined Heat and Power (KWKG) which are responsible for a strong increase of renewable electricity generation and installation of decentralized energy sources over the past years. Accordingly, renewable capacities of approx. 83 GW are currently installed in Germany and up to 30 % of the generated electricity is based on RESs [1]. As a result, overload of distribution grids is already occurring due to strong renewable generation in off-peak demand phases which is counteracted by curtailing RESs. The challenges for ensuring the grid stability and the security of supply are set to increase as 80 % of the electricity production is to derive from RESs by 2050.

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Therefore, energy management concepts are required to cope with the volatile generation of RESs and match electricity production and consumption, through coordination of Distributed Energy Conversion Units (DECUs) i.e. Combined Heat and Power (CHP) and Heat Pump (HP) units.

Methodology

In this section, the concept of 2DSM is introduced. Further, the control strategy is presented, followed by a description of the co-simulation platform. The platform is used to implement the control algorithm and simulate the energy system of a city district.

Concept

2DSM is an approach to manage the electrical and thermal energy demand on a city district level. The aim is to enable the balancing of volatile renewable electricity generation, e.g. PV and wind turbine systems. In 2DSM thermal supply systems combined with thermal energy storages can be operated in a flexible manner to reduce the imbalance between electrical generation and demand. Thereby, the analysis focuses on heat supply systems like Heat Pumps (HPs), Combined Heat and Power units (CHPs) and Electrical storage Heaters (EHs) that are connected to the electrical grid and offer a potential for dynamic control.

The flexible operation of these units is enabled by the availability of storage capacity. Therefore, the technical potential and the economic feasibility of different storage systems mainly hot water tanks and the inherent thermal mass of buildings are investigated in [2–4]. This analysis shows that thermal storage is and will set to remain the most suitable and cost efficient technology. Electrical or chemical storages provide an alternative option for residential DSM, but are very expensive in comparison.

The analysis of using the thermal mass of the building itself as a storage shows promising results. These indicate that a suitable configuration of building type i.e. good insulation standard, heat delivery system e.g. under floor heating and control strategy allows for a considerable storage capacity in the buildings thermal mass without violating residents' comfort.

Control

The energy management scheme is formulated based on a Multi-Agent System (MAS) framework to ensure both the flexibility extendibility and scalability of the control strategy. MAS is a network of distributed software agents that interact to achieve collective tasks. In this system, a complex problem is broken down into smaller problems which are handled by the different agents. The flexibility feature means that the functions of individual agents can be changed easily in order to enhance the functionality of the system or to fix errors. Extendibility is an indicator for removing or adding agents flawlessly from the network. Scalability refers to the option of using the system for small networks as well as for large networks without modification of its functionality.

The execution of the control strategy consists of a scheduling phase for the next 24 hours in 15 minutes time steps and a short time balancing phase that reacts to unforeseen deviations from the operation plan according to the status of the distribution grid. Different scheduling strategies have been investigated in [5]. In this work, the scheduling is based on a cooperative MAS. This represents a demand side management concept in which the DECUs are scheduled collectively to achieve a common goal, while meeting the individual electrical and thermal demand. The corresponding MAS interactions are illustrated in **Figure 1**.

The MAS consists of five agent types with specific functionalities: Weather, renewables, market, buildings, and coordinator. The structure of this concept is kept general with no mapping onto actual stakeholders. Further, no assumptions on the ownership of the functions are made. Moreover, the interaction with other entities e.g. Distribution System Operator (DSO) to check the feasibility of the optimal scheduling is foreseen but not implemented.

The weather agent queries a forecast of the outdoor air temperature, solar irradiation, and wind speed at the location and forwards this information to the buildings and local renewable agents. A building agent uses the outdoor temperature prognosis to forecast the heat demand for the next day and forwards this result to the coordinator agent. The thermal demand forecast is a time series based adaptive algorithm which separates the heat demand into a systematic and a behavioral component [6]. The systematic component is determined by computing a heating curve which correlates the heat demand to the outdoor temperature forecast. The behavioral component is derived from the previously measured heat demand and outdoor temperature.

The renewable agent uses the wind speed and solar irradiation forecasts to determine the expected availability

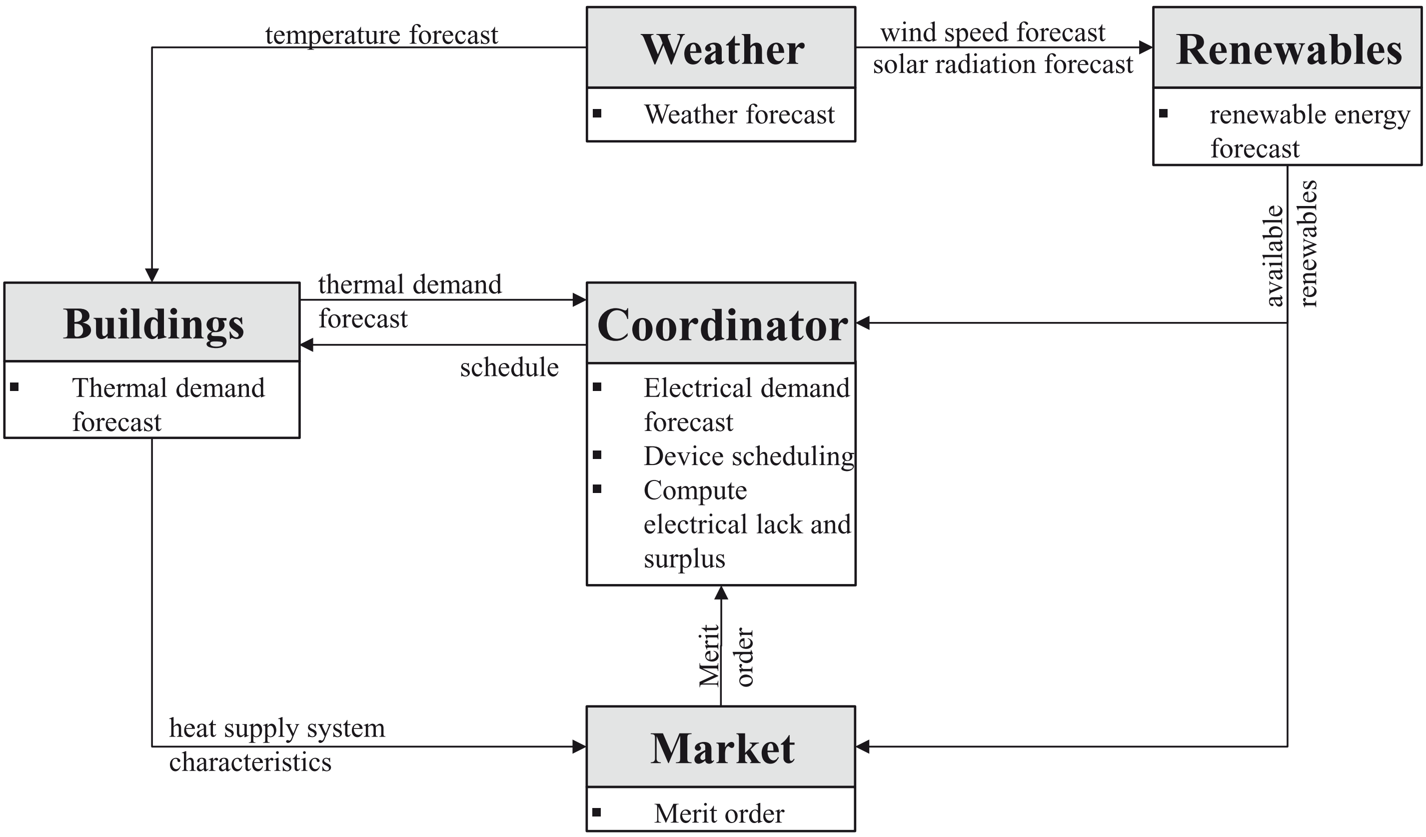

Figure 1. Structure of the multi-agent system.

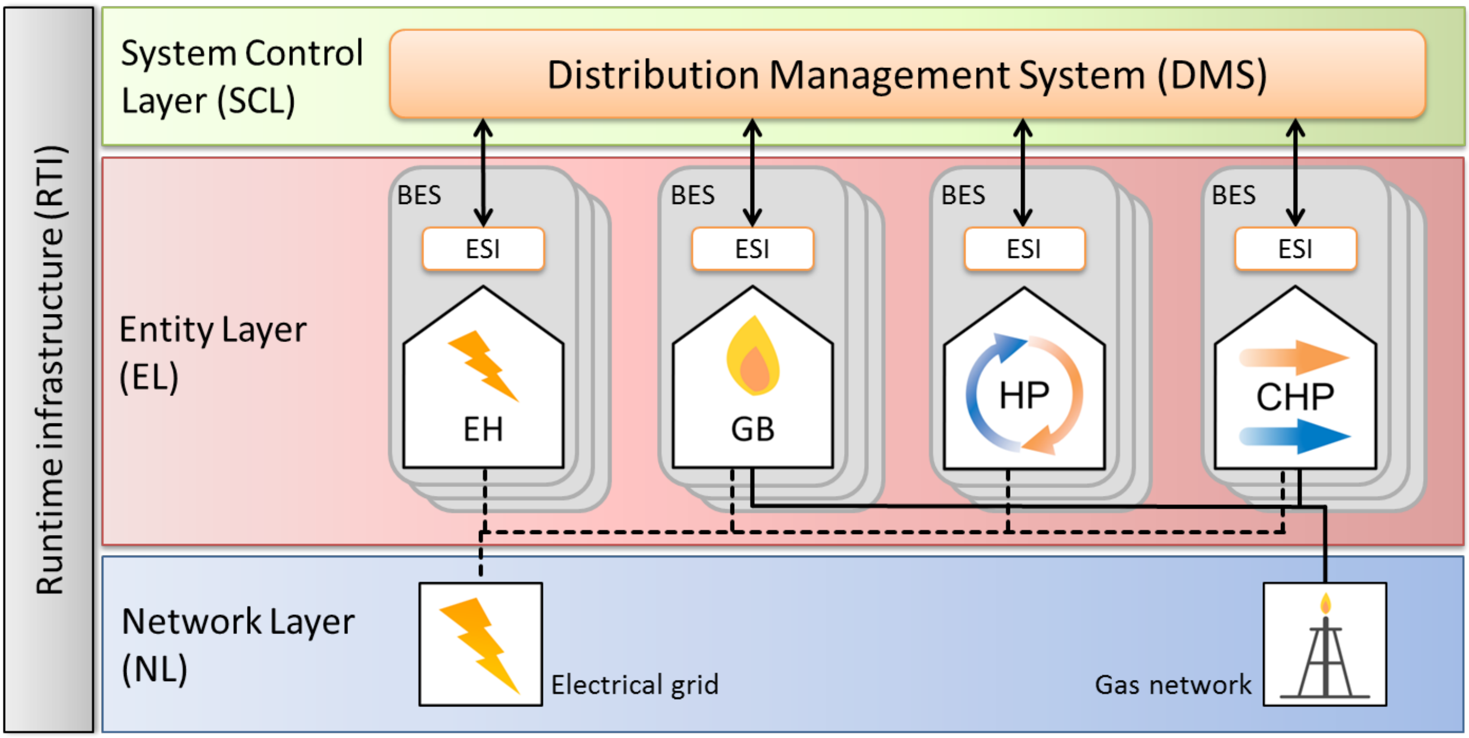

Figure 2. Co-simulation platform for multi-energy systems.

of solar and wind energy and forwards this information to the coordinator and market agents. The building agents send the heat supply systems' characteristics, mainly nominal power and efficiency to the market agent. The market agent determines the price of electricity, based on a merit order system.

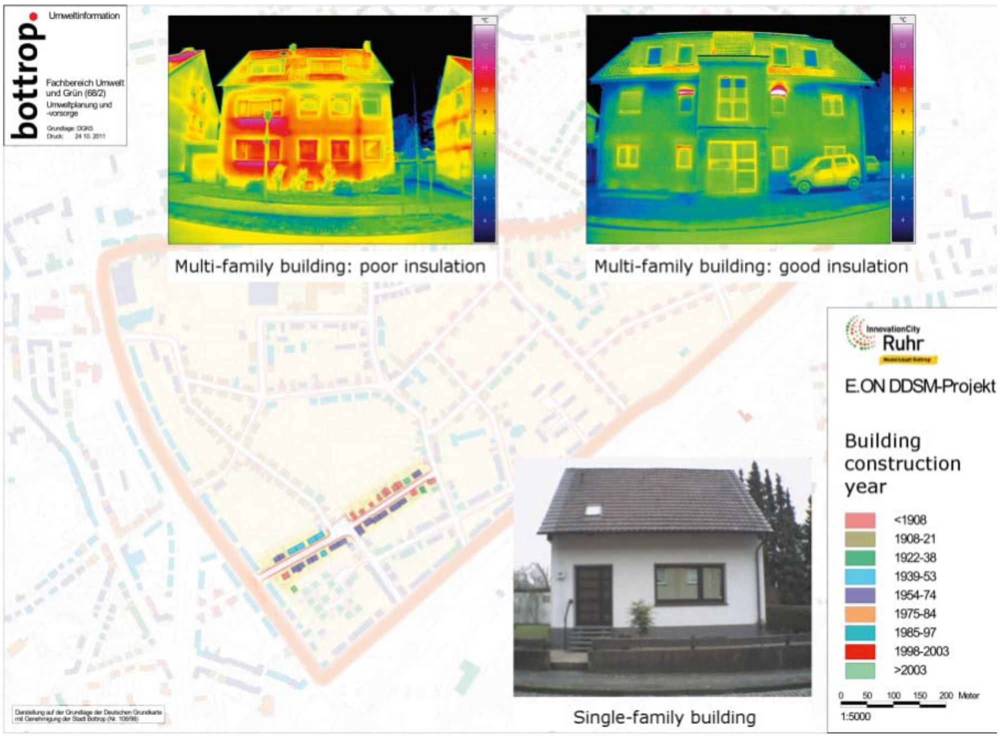

Figure 3. Location, images and age of the investigated group of buildings.

The coordinator makes use of the heat demand forecasts as restrictions for the schedules' optimization. Moreover, the coordinator computes a short term electrical demand forecast based on a double seasonal approach, i.e. daily and weekly, of the additive Holt-Winters method [7]. The Holt-Winters method is an exponential smoothing based model that assumes that the measured demand value can be decomposed into the sum of a level, a linear trend component and a seasonal term. The model presented in [7] is combined with a simulated annealing algorithm [12] to adaptively optimize the smoothing parameters and consequently improve the forecast's accuracy. Simulated annealing is a metaheuristic for global optimization problems, which uses a random driven search technique. The forecast is carried out for all participating buildings collectively, thus reducing the forecast error.

The schedule generation is formulated as a Mixed Integer optimization Problem (MIP) and computed using the solver CPLEX [5]. The objective of the optimization is to maximize the total profit of the participating building agents, which comprises costs for additional electricity and gas, as well as revenue generated from selling electrical surplus and governmental subsidies.

This control strategy is implemented on a multi-energy systems platform which is presented in the following subsection. This enables a co-simulation of the coordination scheme and the buildings' energy supply units as well as the electrical grid.

Implementation

A co-simulation platform was developed to approach the computational challenge for simulating a city district energy system comprising several hundreds of buildings, as well as the corresponding energy supply units and hydraulic systems. The platform makes use of parallel computing features and is based on a modular architecture which allows for the flexible integration of different simulation environments [8]. The architecture is depicted in **Figure 2** and consists of layers for system control, network e.g. electrical and gas grid, and an entity layer. The latter comprises the models of the building energy systems (BESs). The modeling approach of the BESs is presented in [9, 10]. The simulation platform is written in C++. It handles the communication between the different simulation tools. The entity layer's simulation models are programmed in Modelica, the (electrical) networks are modelled and simulated within Neplan and the control layer is implemented in Jade (Java agent development environment).

Investigation

In this section, a small city district comprising 34 buildings is used as a test case to investigate the potential of the energy management for balancing the fluctuating renewable energies and matching the electrical supply and demand.

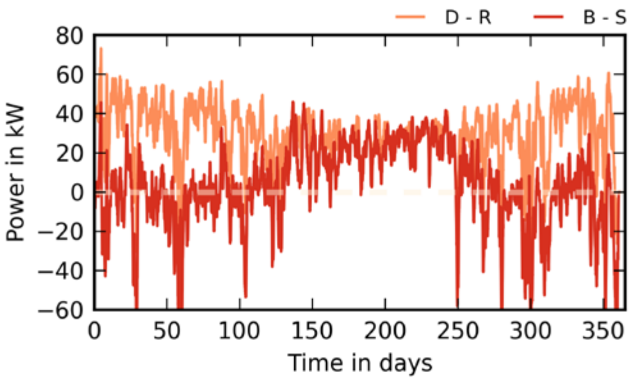

Figure 4. Grid interactions in the heat driven scenario. D-R = electricity demand (D) minus the available renewables (R), B-S = bought electricity (B) minus the surplus (S).

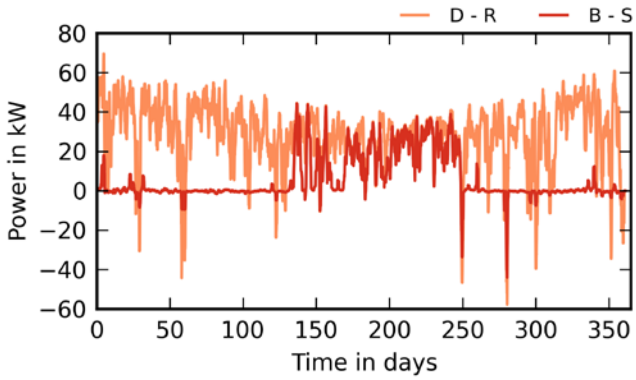

Figure 5. Grid interactions in the energy managed scenario. D-R = electricity demand (D) minus the available renewables (R), B-S = bought electricity (B) minus the surplus (S).

Figure 3 depicts the residential city district which is located in the area Bottrop. The group of 34 buildings comprises eight single family houses, 14 small multi-family buildings with three or four apartments and 12 large multi-dwelling units with five to eight apartments. The number of occupants varies between one to five residents within a single apartment and two to 25 on a building level. The electrical energy consumption for lights and appliances correlates with the number of occupants. Accordingly, the yearly electrical demand ranges between 2 850 kWh for an apartment of two residents and 5 310 kWh for a five person apartment. The profiles are assumed to follow the standard load profile for households and private consumer in North Rhine Westphalia. The thermal energy consumption is mainly related to the construction and insulation standards. The specific yearly energy consumption ranges from 80 kWh/(m^2 a) for well insulated buildings to 290 kWh/(m^2 a) for older buildings as indicated in **Figure 5**.

The buildings are equipped individually with a bivalent air-water HP or a CHP system assuming a parallel operation mode, combined with a heat storage tank. The design and dimensioning of the heat supply system is based on the optimization concept presented in [11] which ensures the economic feasibility of the setup. The simulations are carried out for a one-year period and comprise a reference scenario in which the heating generators are operated in the heat driven mode and a second scenario in which the energy management strategy is implemented.

Figures 4 and 5 illustrate the electrical balance on the grid side. The dark red curve shows the residual demand, which is the *electricity demand ('D')* minus the *available renewables ('R')*. If this line is below zero, the renewable supply is larger than the demand. The light red curve stands for the import or *additionally bought electricity ('B')* minus the *surplus ('S')* which comprises the excess energy of renewables or locally generated electricity from the CHP units. A negative value indicates a surplus which is exported to the grid.

The results of the heat driven scenario are depicted in **Figure 4**. The grid balance displays large peaks of imports and export. This is a clear indication of the lack in coordination. The energy supply units are operated in this scenario to meet the energy demand without any consideration of the availability of renewable energy or the peaks of electrical demands. As a result, it occurs that many CHPs are operated in periods of large availability of RESs which leads to large exports. Similarly, several HPs are activated in periods of large electrical demand, which induces large imports.

Figure 5 depicts the coordination results and the load shifting events of the energy management strategy. In this scenario, the imports and exports are reduced largely. As a result, an almost autarkic status is achieved. The export is mainly restricted to the phases in which a large amount of renewables is available. Additional energy is mainly imported when the demand greatly outweighs the renewable generation or during the summer period in which the CHPs cannot be operated to compensate the electrical demand due to the lack of heat demand and heat storage capacities. When renewables outweigh the demand, the coordination strategy attempts to shut down the CHPs and consequently avoid producing large surpluses. Simultaneously, the heat pumps are activated to take advantage of the availability of renewable energy. In times of high demand, the energy management strategy minimizes the additionally required amount of electricity by deactivating the HPs and activating the CHP units.

Conclusion

This work provides an introduction to the concept of 2DSM as well as its implementation on a multi-energy co-simulation platform. This platform enables the simulation and analysis of city district energy systems comprising a large number of buildings and energy supply units as well as the investigation of the performance of different control algorithms.

The 2DSM energy management strategy is based on exploiting thermal flexibilities for shifting the operation of electro-thermal DECUs to adapt to the fluctuating generation of RESs as well as matching the demand and supply. This allows for integrating large renewable capacity in the electricity generation infrastructure while ensuring the security of supply. Thermal storage capacities are identified as the main enabler of energy management. The inherent thermal capacity of building wall mass is a promising option, however further investigations are needed for the usage of this potential.

A multi-agent system is used as framework for the energy management system to ensure the flexibility, extendibility and scalability of the solution. The investigated control strategy displays a high coordination level allowing for a near autarkic performance. However, it can be foreseen that privacy issues arise with the implementation of such an approach as many input data are required. Moreover, future investigations are needed to analyze the technical implementation of this system. This includes testing of the performance and fault tolerance as well as the communication infrastructure. Additionally, an implementation on embedded systems is needed to pave the way for real life application. ■

Acknowledgement

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