Simulation tool for planning smart urban districts in a sustainable energy supply – integrating several sectors in high resolution

Matthias Stickel¹, Simon Marx¹, Felix Mayer², Manfred Norbert Fisch¹

¹ Technische Universität Braunschweig, Institut für Gebäude- und Solartechnik, Mühlenpfordtstraße 23, 38106 Braunschweig, Germany
² Steinbeis-Innovationszentrum Energie-, Gebäude- und Solartechnik, Gropiusplatz 10, 70563 Stuttgart Vaihingen, Germany

Abstract. A tool for practical planning of smart urban districts has been developed, considering integration into sustainable energy supply. It is based on dynamic energy simulation in high resolution, focusing on sector coupling and individual control strategies in a simple workflow. It provides energy flows and climate balances of individual scenarios. The model includes district grids, all essential supply systems, energy storages and electrolysis (power to gas). The tool was successfully applied to implement an innovative energy concept and to realize one of the first climate neutral operated urban districts in Esslingen Germany.

1. Introduction
The climate policy goals of the EU aim at an environmentally friendly, safe and cost-effective transformation of the energy supply. The solution can be found in the expansion of renewable energies and is subject to the challenge of dealing with their fluctuating behavior. The building sector plays a key role in the process of energy transition, especially since the previously pure consumption characteristics have changed and buildings take on an increasing share of the demand-oriented provision of heat, cooling and power themselves [1][2]. For the benefit of systemic interaction, it makes sense to group together several buildings, whereby the maximum exploitation of available renewables through a sector coupling (power, heat and mobility) is achieved [3][4]. According to the requirements of a sustainable supply concept, the district should not be thought of as an autarkic island, but an interactive, grid serving connection to the public grids (especially power). In order to enable a constructive exchange (e.g. the import of fluctuating renewable surplus power), the district must be able to act in the same time intervals in which the boundary conditions of the grid vary over time due to the volatility of renewables.

To determine the energy demand and to map supply scenarios at urban district level, a wide variety of approaches with different emphases were created (e.g. CitySim [5], SimStadt [6], TEASER [7], CEA [8]). Typically, the focus of the approaches is either a rough or limited model with simple handling, manageable modelling effort and simulation time or an extensive dynamic simulation in high resolution using a complex multi-software workflow. Furthermore many tools focus on an overarching (up to city) level. For a successful energy transition towards a highly renewable energy supply, however, grid-serving sector coupled districts must be planned and implemented in large numbers. A comprehensive implementation of such districts is only possible with planning tools that balance simple handling for applied engineering practice with a high-resolution energy flow calculation on a specific district supply
system level. In a previous investigation of district simulation tools ([9] [10] and others), no tool was found that fits these requirements.

In the project “Climate Neutral City District - Neue Weststadt Esslingen” therefore a planning tool for early design process of urban district supply conception was developed. Under the premise of universal applicability, it is based on free or widely distributed software. The tool focuses on sector coupling and extensive possibilities for individualized control strategies, necessary to model a smart grid. The approach follows a simple workflow. After creating the basic energy demand profiles and photovoltaic potential profiles (see chapter 2) the district can be modelled and simulated (see chapter 3) as the following sequential flow chart shows:

![District simulation - sequential workflow](image)

**Figure 1.** District simulation - sequential workflow

### 2. Generic thermal building simulation

In an initial system definition, the considered district must be spatially delineated and the included buildings must be divided into typological reference buildings. The division can be made according to the essential distinguishing features in terms of geometry, construction standard, use and HVAC system. In order to include the energy demand and the solar potential of the urban district accurately in its dynamic behavior, the identified typological buildings are subjected to a thermal building simulation. For this purpose, a generic approach has been developed, parameterizing a standardized EnergyPlus™ building model via a simple Excel® input mask. The simulation of each reference building delivers dynamic demand profiles for heating, cooling, user power and PV production in high resolution (see Figure 2). To facilitate the user input with default values, extensive databases have been created providing user profiles, internal loads, air change rates and more [11][12][13][14][15].

![Generic building simulation - providing demand profiles for district simulation](image)

**Figure 2.** Generic building simulation - providing demand profiles for district simulation
3. District simulation

3.1. Model-structure

The model-structure was developed with the aim of providing the most simple but flexible way of modelling different types of urban districts connected with individually designed smart grids. The result is a model-structure, grouping the district into generic building-blocks on first level (see Figure 3 top right). A single block defines the buildings and likewise the energy systems inside the block.

On second level each block consists of zones representing the buildings’ energy demands (Figure 3 bottom left). For each zone the energy demand is defined by assigning load profiles, previously generated in the first step of the district simulation workflow (see Figure 2). The profiles are based on the area specific net energy and are scaled in each zone by defining the zone-area. For each specific demand in a block, the sum of all zones is formed. In practice the definition of blocks and zones can be made individually. For example a block could either be a single mixed use building with zones representing the different usages (e.g. residential, office and restaurant) or it could be a couple of buildings with zones representing different reference buildings. For modelling central energy systems a block can also be used without zones/demands, just containing energy systems.

A block can include up to 5 heat generators, individually connected with thermal storages for supplying heat- and DHW-demand (domestic hot water). CHP (combined heat and power) systems, heat pumps, boilers using several fuels and solar heating are available types. CHP systems additionally produce electrical power that can be used to supply the blocks and/or the districts power demand. With exception of CHP systems all heat generators are heat-controlled by default. CHP systems can play a major role in a district supply concept realizing a smart grid. Typically pure heat-controlled operation of CHP systems is not constructive in a smart grid, because it is not coordinated with other electric power gains like PV. By reserving parts of thermal storages, the operation of a CHP system can be shifted into times with high uncovered power-demands (e.g. in times without PV gain), whereby the direct use of the electric power generation can be maximized without reducing full load hours. Such operation modes for CHP can be alternatively selected as defaults in the model or even individually designed. Heat pumps and chillers produce a power demand while operating that must also be supplied by internal or external sources. All district power sources – PV, Wind and CHP’s – can be combined.

**Figure 3.** Generic district/block model structure
with centralized or decentralized batteries. Additionally, an electrolysis can be used for taking surplus power from the district and renewable energy from the public grid, producing hydrogen and waste heat that can be used to supply heat demands in the district. By defining district grids, connecting blocks especially for heat and power, and individual control strategies (see following chapter), centralized and decentralized supply scenarios in a smart grid can be modelled as well as an individual mix of it. Besides energy flows the simulation also automatically calculates the CO₂ balance using individual CO₂-equivalents.

3.2. Basic modelling approach and control strategies

The model has been developed from scratch based on an object orientated programming approach using Visual Basic for Applications (VBA). The major advantage of VBA is the potential to quickly create a user-interface via Microsoft Excel®. The model is based on simple energy balancing to cover the assigned demand profiles. It is extended by temperature dependencies if necessary, using additional temperature-profiles. For example to calculate the efficiency of a heat pump that has a dynamic heat source temperature (e.g. ambient air), a temperature profile of the source is assigned. With help of the profile, the dynamic efficiency for each time step can be calculated. Further temperature dependencies were necessary for modeling solar absorbers, chillers (equal to heat pumps) and for losses of thermal storages. The default time-step width for simulation is a quarter hour, however others are possible.

A linear simulation sequence is realized, whereby the energy fluxes are calculated and energy demands are successively covered by the different energy sources in each time step. The sequence is a line of model functions, representing basic functions of the district supply system (Figure 4 left). The order of the simulation sequence can be individually defined. Thereby the basic control strategy of simulation is statically determined for the whole simulation period, respectively the basic order of energy generation, energy usage (direct and indirect by loading storages) and demand covering.

![Figure 4. Basic Structure of individual simulation sequence and relation to control strategies](image)

Each model function is calculated for each single building block before executing the next model function. If the model function is using district grids, the order of execution on block level is individual because it is determining the order of coverage on district level (Figure 4 middle). Finally, there are possibilities to define control strategies inside each single block (Figure 4 right). These are basic merit orders supplying the block demands, parameters to control storage-management, operation strategies for heat-generators and chillers and “Power to X” using internal and external surplus energy.
4. Simulation of the climate neutral and grid serving urban district “Neue Weststadt Esslingen”

The urban district "Neue Weststadt Esslingen" is realized in the superior research project to be one of the first climate neutral operated and highly grid serving urban districts in Germany. It consists of three building blocks with focus on residential, office and university. The district is connected via a power- and heating grid supplemented by a central power station. The overall idea of the energy concept is the import of regional and cross-regional renewable power surpluses from the public grid with an electrolyzer and the local power generation and grid feeding using a CHP, in times with low ratio of renewable energy in the grid. The local generation of electrical power with photovoltaics (PV) and the priority of maximized self-usage (including e-mobility) supported by a battery form the basis. The heat demand of the district is to be mainly covered by the waste heat of the electrolysis and the CHP. The generated hydrogen will be used for local industries, refueling of hydrogen vehicles and gas grid feed (as an important contribution to the decarbonization of the existing building stock).

With help of the district simulation, system sizing and evaluation of the concept and operating strategy was done. Below the model and simulation is discussed showing three representative days of an exemplary quarter hour simulation (see the following figure).

![Power controlled operation of the district smart grid (Quarter hour simulation)](image)

**Figure 5.** Example results of simulation illustrating the basic control strategy and the potential of district simulation

The volatile, non-controllable gain of PV is primarily used to directly supply power demands in the district. Surplus PV gain is collected from the central battery storage supplying the district with a time delay (Figure 5 top diagram blue line/bar). The last path for PV surplus power inside the district is the electrolyzer (Figure 5 top diagram dark green). To simulate the grid-controlled power consumption of the electrolyzer from the power grid, an individual pre-defined surplus-power-profile was used (see Figure 5 bottom diagram) based on market price. Reason: Previous studies of historical German grid data have shown that there is a strong correlation between market price and the ratio of renewable energy (low price meaning high ratio). The operation strategy of the CHP is a mix of power optimized and heat controlled operation (see also chapter 3.1). CHP operation takes place mainly accounting the uncovered districts’ power demand (after PV and battery coverage) and the potential to charge the battery, but is constrained by heat usage (no chiller) and in case of critical heat storage level also heat controlled (Figure 5 top diagram green). Second, the CHP operation strategy accounts the market price for grid feeding, using another individual pre-defined profile. In the example, the battery charging through the CHP is limited to 50 % of usable SOC (state of charge) instead of PV that can fully charge.
5. Conclusion
The aim was to provide a tool for practical planning of urban district supply systems in the early design phase. Focus is sector coupling and individual control strategies to model a district smart grid. After evaluation of existing software, a new tool was developed based on a simple energy balancing modelling approach allowing dynamic energy simulation. In the superior research project, in which a climate neutral operated and highly grid serving urban district with integral sector coupling in Esslingen Germany is realized, the tool was successfully applied to turn the energy concept into practice. With help of the simulation results it was possible to evaluate the supply and control concept and to provide a system sizing basis for the further planning process. Appropriate results could be achieved without the use of detailed physical models, taking into account the inaccuracy of highly sensitive input parameters (especially demand profiles) in an early design phase of the district conception. The tool was developed for small and medium size districts on a specific district supply system level. It is not suitable for spatially extended analyses. Technical limitations of the model arise due to the simple model approach. Detailed results within a system component (e.g. pressure and temperature in a heat pump) are not the aim of this development. Rather, the superordinate relationships especially energy flows in complex, sector-coupled energy supply systems are to be investigated. Next steps will be a validation with monitoring data and a cross-validation with other comparable tools as well as the dissemination in engineering practice.

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