OPTIMIZATION OF LOCAL RENEWABLE ENERGY SYSTEMS USING AUTOMOTIVE SIMULATION APPROACHES

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ABSTRACT

With the rising individual demand for energy as well as the diminishing fossil energy resources, new optimized concepts for energy supply and usage are required for future buildings. To address these challenges, renewable energy sources and decentralized storage are matters of rapidly growing importance.

Electric mobility concepts and electrical vehicles address these challenges but provide additional requirements due to power and energy demands. Thus future building energy systems have to integrate successfully user demands, local renewable energy, storage systems and charging infrastructure, a task requiring extensive scrutineering.

This paper describes an approach of simulation-based analysis and optimization with Modelica, as widely used in the automotive industry, for the design of building energy systems. Furthermore, exemplary results for the application of the optimization-tool-chain are shown.

INTRODUCTION

Conventional building energy systems have to fulfill the task of satisfying the heat and electricity demands of the inhabitants. Most energy and power are supplied by the public grid or fossil fuels.

Today, this is changing. Ecological footprint, detail efficiency as well as usage comfort are matters becoming more important. To fulfill these aspects, various components like photovoltaic or storage tanks, even weather forecast, need to work together to provide the users demands renewably and reliably.

Besides the technical aspects of automation and networking systems, the functionality of this component interaction needs to be clarified.

One exemplary question to answer is the best combination of energy components like micro-wind-turbines, photovoltaics, solar heat, heat pumps as well as combined heat and power units (CHP) at a specific location. This answer may also vary depending on available monetary budget.

No matter how high the financial budget is, renewable energy is limited in availability. The peak PV-power is at noon while peak consumption is often in the morning or in the evening. A question to be answered is whether it is better to store the energy in batteries, to change the PV-alignment towards east or west or to move energy intensive tasks to lunchtime (virtual storage).

Maybe it is even possible to use the batteries of electric vehicles as storage, as long as the cars are not empty when needed or these expensive components are not aged much too fast. Of course, charging stations need to be available at the building.

All these aspects show the high degree of freedom in the system of energy producers, storages and consumers. The algorithms of the needed energy management systems as well as smart-grid technologies add even more free parameters.

With all this smart stuff, the user acceptance and interaction is essential to the system, affording a good visualization and usability.

As shown, an ecological as well as economical worthwhile layout of the next generation building energy systems is a complex engineering task. Creating energy management for these systems is as difficult.

SIMULATION PLATFORMS

To cope with these difficulties, a dynamic simulation covering all macroscopic aspects of the whole system is needed. In the automotive industry, the application of such simulation-based analysis and optimization of software and hardware is widely used. Complete vehicle models to test system behavior are state of the art.

For buildings, depending on project size and scope, there are different simulation systems available. One group covers component simulators to layout subsystems like PVSol for photovoltaics. These have huge module and inverter databases and allow for highly detailed economical and efficiency evaluation.

A second group validates consumption according to law, energy reduction regulation EnEV for Germany.

A third group of tools uses FEM and CFD. These make it possible to simulate heat and radiation input to complex rooms and buildings and to calculate the resulting temperature fields, air flow, etc. Ansoft ANSYS and Autodesk Ecotect are examples for these.

A fourth group addresses systems simulation. HVAC, even photovoltaics and wind are integrated into one block oriented system model. The underlying physics are often represented as equivalent networks while control algorithms are represented in a signal oriented way. A typical tool-chain would contain TRNSYS and Matlab Simulink. These toolchains are extraordinary powerful. Yet some important effects like the nondeterministic behavior of humans, electric mobility, dynamic cost, battery aging and probability based energy management systems have been difficult to implement.

Object oriented multi-domain simulation and the combination of modeling and programming are disciplines where the Modelica language excels and is widely used in automotive technologies.

This paper describes an approach to adapt this to building energy systems.

The presented tool under development is able to simulate and evaluate the energy flow in a future building energy system with integrated charging stations for e-Vehicles. It can be used to layout the most energy and cost efficient combination as well as to test intelligent energy-management-algorithms.

CONCEPT FOR ENERGY SIMULATION

Given a set of input parameters, like location, building usage, weather or available budget, the main idea is to test possible energy system configurations under simulated typical usage and stress conditions.

Particularly, the interactions between subsystems and users as well as between domains like heat, electricity and cost are of interest. This way shortcoming of a specific configuration can be identified and optimized by finding the relevant setscrews. This is especially useful where rules of best practice cannot be applied or are simply wrong.

For example, snowy weather has influence on solar input as well as heat demand, but the heat demand changes drastically if weather is so bad that people leave earlier for work or cannot leave the house at all.

To simulate a complete building energy system, the main idea is to implement the physical behavior of the components as well as control strategies, external behavior and cost functions into one set of differential and algebraic equations (DAE).

It is easy to see, that the resulting set will be huge, containing descriptions of different scientific domains. To handle this, a domain-overall simulation library for building-related energy systems has been built, based on Modelica in the SimulationX environment. Modelica's non-causal modeling helped to efficiently create this set of typical components needed.

It contains subcomponents and control structures for thermal and electrical energy consumers, producers and storages. With this library, most different types of renewable energy systems can be simulated with a huge set of arbitrary component-specific parameters. Yet, thanks to the object-oriented structure it remains easily understandable. Currently, the library provides the following models:

- User
- Electric vehicles
- Stationary battery and heat storage
- Combined heat and power unit (CHP)
- Heat pump
- Photovoltaics
- Solar heat
- Micro-Wind-Turbine
- Building model
- Hot water system
- Local electrical grid and external grid connection

Fig. 3 shows the generalized layout of these components. Each consists of four specific subcomponents:

- Phenomenological or physical behavior
- Operating strategy
- Cost calculation
- Sensors and interactive connectors

In the first part, the behavior of a component is modeled with respect to simulation speed. This is required to simulate the long time periods needed to generate synthetic usage statistics and to identify the shortcomings of the system (i.e. probability of insufficient heating).

The second part describes the operating strategy of the specific component. This includes the energy-flow-related control-algorithms of the component (i.e. max-power-point tracking in photovoltaics) as well as functionality needed for error free operation of the components (i.e. periodic de-icing-process of a heat pump). Additionally this part integrates the intervention of a building-overall energy-management-system (i.e. thermal power set point for heat pump).

The third part of the model contains an algebraic equation system for cost calculation. This covers acquisition and maintenance as well as energy-flow-depending operating costs and amortization.

The parts are connected internally and to other components using domain-specified energy-representing connectors (heat flow, alternating power, etc.) as well as sensor templates and control flow (set points). These are defined in the library as well to improve handling and to minimize mistakes.

Reduction of Complexity

As mentioned above, calculation speed is essential. The best way to improve this is a reduction of complexity.

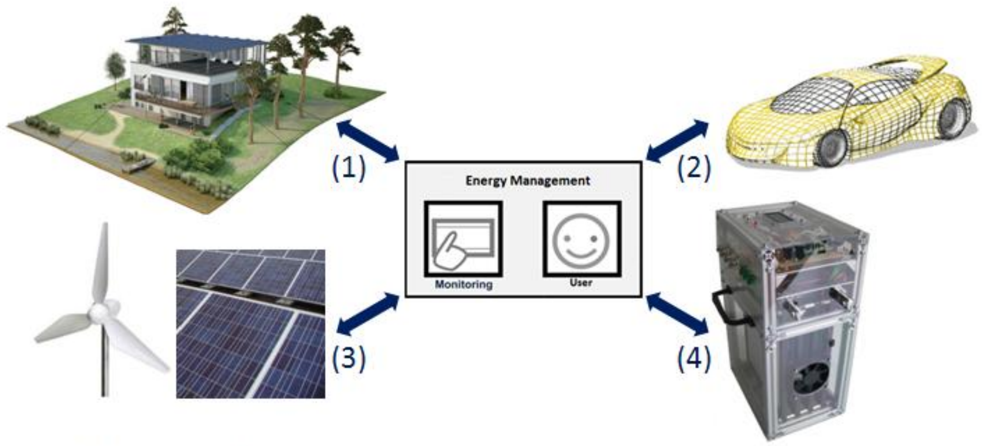

Fig. 1: Future building energy system including modern building architecture (1), eVehicle charging point (2) renewble energy production (3) and decentralized energy storage (4)

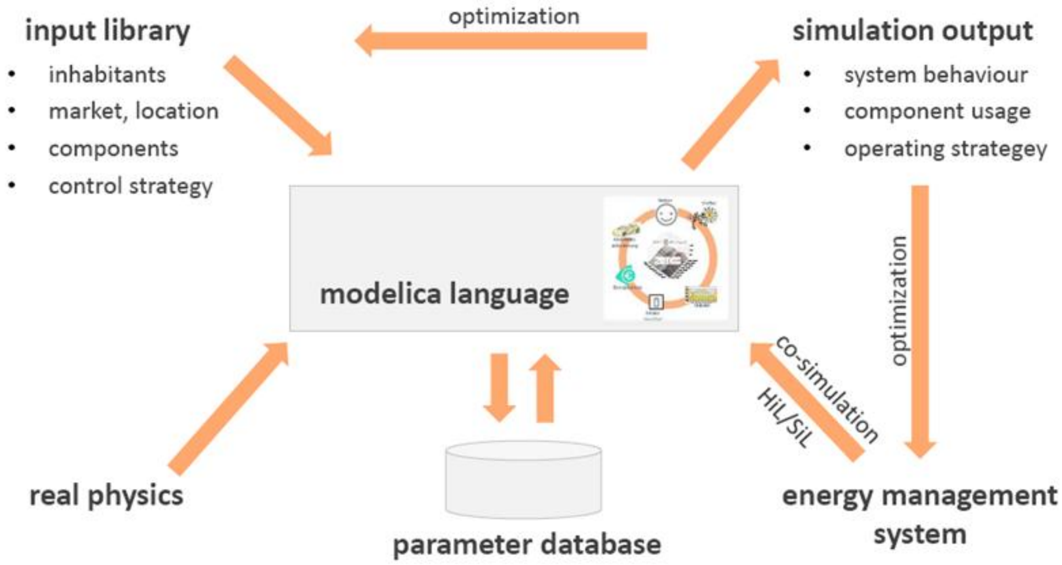

Fig. 2: Basic concept of the holistic energy simulation system

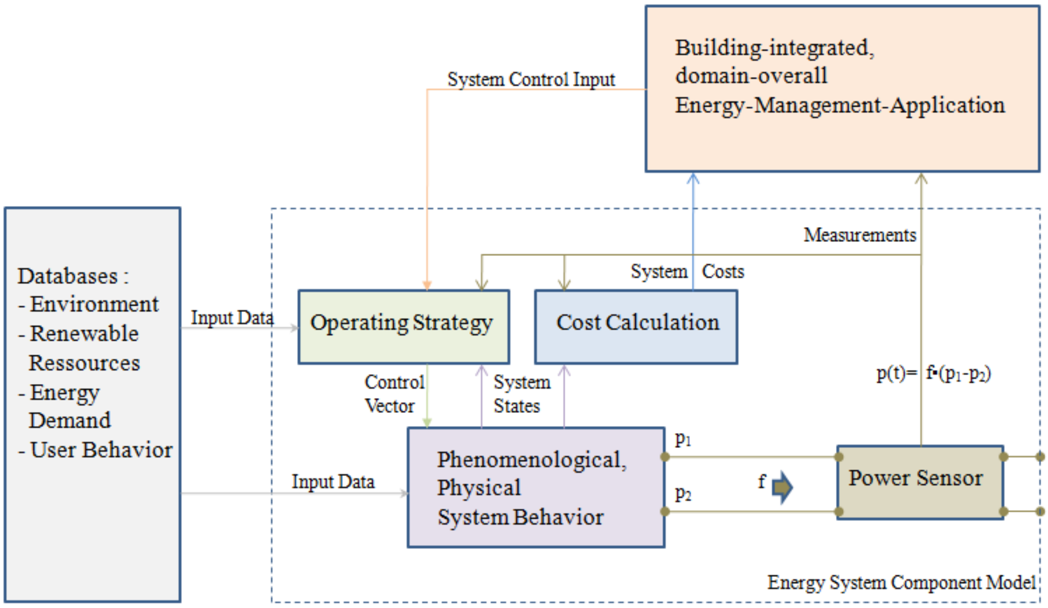

Fig. 3: Energy system component model concept including sensors, cost calculating and strategy blocks as well as interfaces to energy-management-application and databases

From simulator or especially solver point of view, a reduced complexity means: less independent variables, less equations and lower degree of the equations.

To get the models fast, one approach is to neglect the internal relations and to describe the phenomenological behavior as a black-box system. This can be done with a set of precalculated operating points depending on the outer characteristics. A finite automaton based on states switches between these operation points, for example an air-water heat pump switches based on outside temperature. Given this, a reduced differential algebraic equation system (DAE), is enough to sufficiently describe the energy-flow related behavior like COP depending on feed and return temperature.

Another possibility is to simplify the internals. A wind-turbine, for example can be reduced to a characteristic curve of grid power vs. wind speed and some first order dynamic, neglecting the internal fluid dynamics, electrical machine and power electronics.

Complexity can be reduced further by minimizing the interconnections between the single components. For the building energy system these are mainly control structures and the energy or power-specific characteristics defining component interactions.

$$(1) \quad e_{therm}(t) = \int c_{p_{med}} \cdot \rho_{med} \cdot \dot{V}_{med} \cdot \Delta T_{med} \, dt$$

$$(2) \quad e_{el}(t) = \int \cos\varphi \cdot n_{phase} \cdot U_{eff} \cdot I_{eff} \, dt$$

The two equations describe the energy transport for heat (1) and electricity (2). These are the basic relations to connect thermal components like heat storage and heat pump or electrical components like photovoltaics and the local electrical grid. The two definitions are consistent and well-arranged using one potential characteristic (voltage or temperature spread), one flow characteristic (current or volume flow) and conduction-specific characteristics, like number of phases, power factor, medium density or heat capacity.

Component Example – Building Model

The library focuses on renewable energy components, storage, mobility and cost. It is linked to the actual building by electricity (light, ventilation, etc.) and heat demand of the different sections (current, flow and return temperature) as well as internal storage capacities. For large buildings these need to be linked to detailed black-box models or precise tools like TRNSYS.

If the main focus is on renewable energy system layout, use and storage, it often is sufficient to represent the thermal behavior by a number of single zone rooms. This allows for a consistent optimized model structure within the Modelica environment. Additionally this avoids performance and monetary cost for additional tools and simulator coupling.

In the preprocessing, the room list of the building is divided into zones with similar usage and general conditions (e.g. heights (3), comfort temperatures (4) etc.).

$$(3) \quad h_{zone} = \frac{\sum_i A^i_{room} \cdot h^i_{room}}{\sum_i A^i_{room}}$$

$$(4) \quad T_{zone} = \frac{\sum_i V^i_{room} \cdot (T^i_{room} - T_{amb})}{V_{zone}} + T_{amb}$$

These single zone rooms are considered well mixed and internally energy-equal. Fig. 4 illustrates the covered effects for such a room. The number of these is a decision between simulation effort, calculation time and precision.

Basically, the actual heat load of a building depends on the difference between the room temperature and the ambient temperature, the resulting losses across the building envelope in combination with outer and inner heat yields. The actual stored heat in the building is calculated with standard coefficients:

$$(5) \quad Q_{room} = (\sum_i c^i_p \cdot \rho^i \cdot V^i) \cdot (T_{zone} - T_{amb})$$

Masses within the building envelope like walls and basements are simplified as additional heat capacities with temperature equal to the room.

The room envelope is parameterized using coefficients for heat convection, etc. For walls, windows, roof and floor different coefficients can be used. With these coefficients (U) and statistic factor (S) considering the absorption of shortwave radiation [cf. Steinborn, 2002], the transmission losses for a specific building element can be described by (6):

$$(6) \quad q_{trans} = \sum_i S_i \cdot U_i \cdot A_i \cdot (T_{zone} - T_{amb}) + \sum_i C_i \cdot V_i \cdot \frac{d(T_{zone} - T_{amb})}{dt}$$

The second equation term handles the first order dynamic of the heat storing behavior of this part of the building envelope. Factor (C) includes characteristics like wall masses and specific heat capacities.

Another important thermal loss is caused by heat bridges across the room envelope. Reasons are less insulated building elements, lead-throughs, etc. To keep model complexity within a limit, the heat bridge losses calculation uses a statistic factor (U_{HB}). Otherwise it is similar to transmission losses across a further building element (7) [Krause, 2007]:

$$(7) \quad q_{HB} = U_{HB} \cdot A_{OW} \cdot (T_{zone} - T_{amb})$$

A comfortable room climate needs an adequate air change rate. This variable change rate (L) depends on room usage and presence of inhabitants. (L) The energy loss (8) also depends heat recovery rate ($R_{\%}$) if controlled ventilation systems are installed [cf. Steinborn, 2002].

$$q_{vent} = c_{p_{air}} \cdot \rho_{air} \cdot V_{zone} \cdot L \cdot R_{\%} \cdot (T_{zone} - T_{amb}) \tag{8}$$

This can be modeled in more detail using humidifiers, heat exchangers and electrical power for forced ventilation. Again, this decision should be made depending on system complexity, calculation time and required precision.

Besides heat losses there are also inner and outer gains. Examples for inner heat gains are people, artificial light and usage of electric devices. These are modeled using trajectories for usage and power factors.

External gains caused by transmission from the heated wall surface (6) and by solar radiation through the windows (9).

$$q_{sol} = \prod_j w_j \cdot \sum_{i=1}^{4} g^i \cdot A_W^i \cdot I_{vert}^i \tag{9}$$

Basically, normal radiation (I) through the window area (A) with permeability (g) is calculated for each outer wall. Additionally statistic correction factors for window soiling etc. are included [cf. Steinborn, 2002].

The heating system is integrated into the room as a radiator model. This way, the most important effects which are responsible for the temperature in the building are represented in one simulation model.

Radiator equation (10) shows the relation between actual (q_{HT}) and installed power of the radiator ($q_{install}$) in relation to room (T_{Zone}), flow (T_V) and return (T_R) temperature as well as the nominal Temperatures for the radiator. The exponent (n) describes the behavior of differing radiator types, like underfloor heating or wall radiators [cf. Recknagel et al., 2010].

$$q_{HT} = q_{install} \cdot \left(\frac{\dfrac{T_{V,op} - T_{R,op}}{\ln\left(\dfrac{T_{V,op} - T_{zone}}{T_{R,op} - T_{zone}}\right)}}{\dfrac{T_{V,nom} - T_{R,nom}}{\ln\left(\dfrac{T_{V,nom} - T_{zone,nom}}{T_{R,nom} - T_{zone,nom}}\right)}} \right)^n \tag{10}$$

The relations (5) to (10) are aggregated in the Modelica code for the single zone well mixed room model. Combined with the models for the electricity and heating subsystems, the simulation platform builds the complete system set of differential algebraic equations. Since no tool coupling is needed, the platform can use efficient variable step size solvers for transient simulation.

Another important aspect of the non-causal modeling approach is the direct feedback to the other components. For example, room temperature changes radiator return temperatures or heat pump efficiency. This way, shortcomings of the system can be identified and energy management algorithms can be tested. Although influences like change of flow temperature on the system performance can be tested.

Integration of databases and energy-management-algorithms using FMI

Simulation results depend on the quality of input data (i.e. local climate, weather, planned usage). Yet exchanging detailed trajectories between preprocessing and Modelica is difficult. Currently external tables with coarse trajectories and parameters for generated overlay signals are used. A better way is to use fine trajectories which are stored in an external database.

A second aspect is the set of management algorithms as an integral part of the energy system. Whether to store generated electrical energy in batteries or as heat via heat-pump is a typical decision. This can be complicated arbitrarily. With the system model in place, the idea is to use the simulator as a virtual environment for the energy management (Software-in-the-Loop). This way the real software can be tested under a wide variety of circumstances [Schubert et al., 2011].

Both tasks need the same kind of interface, which is currently under development. Modelica offers different possibilities. One is the external object interface using external C-functions.

The other possibility is FMI (Functional Mockup Interface) which is a new standard for data and model exchange defining an interface for different types of simulation environments as well as embedded control systems. It describes a set of functions and parameters implemented in a binary file which is complemented by an XML-file with descriptions of the models and their parameters.

In this, FMI would be ideally suited for the connection of management software as well as input-databases (see figure 5). Since variable step size support is not fully supported in FMI yet, the external object interface was used for the current implementation.

In the first implementation, the underlying C-Library calls the energy management system (Java App) via socket connection. In the second implementation, the C-Library encapsulates SQL directives for the database and interpolation algorithms.

EXEMPLARY SIMULATION RESULTS

The example is a luxury single family home in northern Germany with indoor swimming pool. This building illustrates some major aspects of the simulation, yet it is simple enough to compare the results to the classic design process.

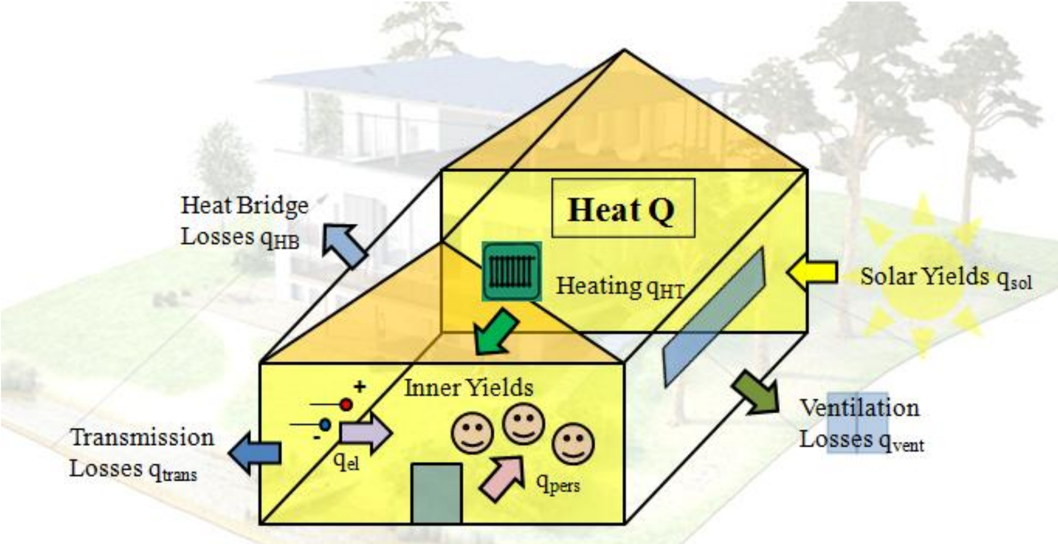

Fig. 4: Heat Flow across and inside the building envelope

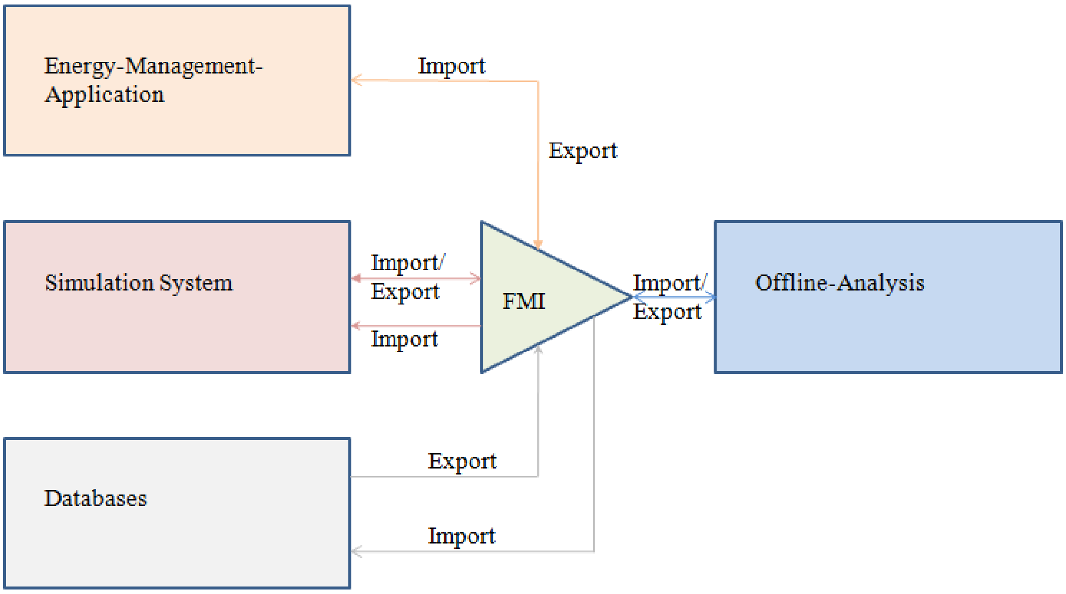

Fig. 5: Tool-Chain using FMI for connecting databases and energy-management-application (SiL) as well as offline-data-analysis functions to simulation system

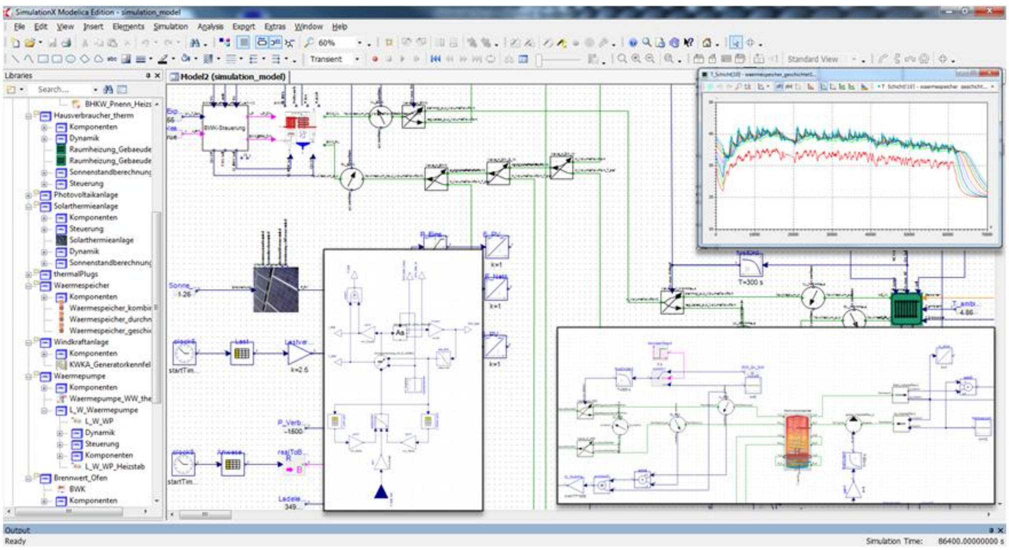

Fig. 6: Screenshot of the simulation model including the used libraries

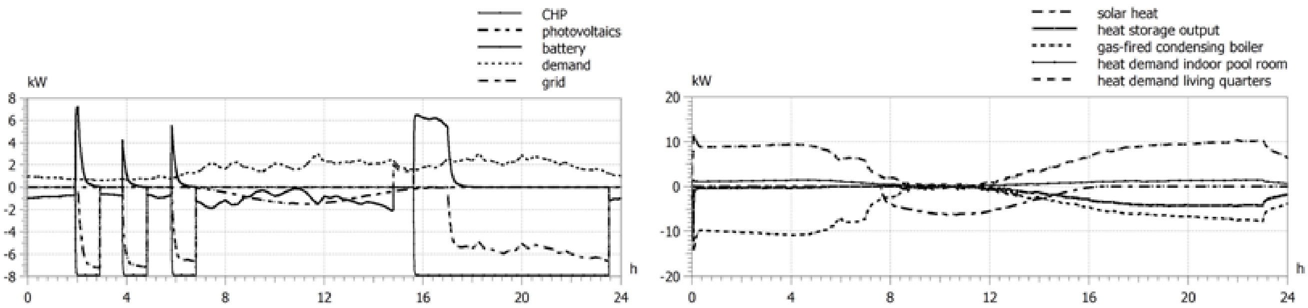

Fig. 7: Simulated electrical power for system configuration: CHP, Photovoltaics, Battery, Heat Storage (left) and simulated thermal power for system configuration: gas-fired condensing boiler, Solar Heat, Heat Storage (right) for a sunny day in spring

Based on the structural and economical boundary conditions two possible configurations have been under consideration:

- Combination of natural-gas-fired condensing boiler, solar heat and heat storage
- Combination of photovoltaics, battery, CHP and heat storage tank

The task was to identify the most energy und cost efficient configuration under real-world usage conditions. The two system configurations were modeled using the predefined components of the simulation library. Both configurations contain an electric vehicle driving an average of 30km in the morning.

The first system is outfitted by a gas-fired condensing boiler with modulated power output from 3kW to 24kW, a 5.66m^3 Mixed-Temperature-Heat-Storage and an 18m^2 CPC-Solar-Heat-Collector.

The second system includes a combined heat and power unit (18kW rated thermal output, 8kW rated electrical output), a 5.66m^3 Thermally-Stratified-Heat-Storage as well as a photovoltaics system rated at 2.64kWp and a lithium-ion-battery with 10.8kWh maximum storage. The heat storage tank is needed to achieve high a thermal cover ratio of the CHP.

The heat demand of the building is simulated by a simple 3-subzonal-room-model including living quarters, indoor pool and garage/storage area. Electrical energy demand and power characteristics are derived from a comparable season-specific scenario. Conditions outside are based on data from a nearby weather station.

Both scenarios share a similar energy-management-algorithm, since this is essential for the results. The basic rule is to charge the building-integrated storage systems only with local renewable energy. This way the heat storage in the first system will only be charged by solar heat and discharged if storage temperature is above a minimum level.

The battery in the second configuration will only be charged by the photovoltaics system or the CHP when the energy production is higher than the demand. The stored energy is used to satisfy the electrical power demand when local renewable power is not sufficiently available.

Fig. 7 shows the simulated electrical power of the second configuration (PV, CHP, battery) as well as power demand and grid power for a sunny day in spring. In this configuration the whole electrical power of the photovoltaics system can be instantly used locally. No power has to be taken from grid for the whole day. Actually, more than 50% of the energy is fed to grid. The reason is the peak of heat demand in the morning and in the evening. This heat was provided by CHP while the electrical power was not needed and therefore fed to the grid.

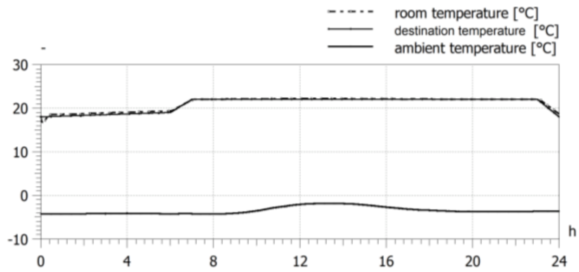

Fig. 8: Simulated temperature characteristics

Storing this energy would multiply battery costs but should be welcomed in the grid during peak hours. Rated CHP power was determined by the heat demand of the considered building at times with low ambient temperature. The simulated temperature behavior of the house at such a cloudy winter day is presented in fig. 8. Evidently, the simulated room temperature follows the comfort temperature in the house within the design boundaries.

Fig. 7 (right) also shows the simulated heat demand of the house and the indoor pool room as well as provided thermal energy by solar heat, heat storage and gas-fired condensing boiler for a sunny day in spring.

During the morning hours the heat demand is only satisfied by the gas-fired condensing boiler. From forenoon till late afternoon no gas is needed to keep room temperature at comfort level. The thermal energy collected during this time is stored and used to support heating the house during the evening.

Both system configurations are designed to sufficiently fulfill the electricity (30kWh/m^{2}a) and heat (125kWh/m^{2}a) demand of the described building. The high heat demand results from usage with indoor pool, comfort temperature (21-23°C) and ventilation losses (initially user did not want heat recuperation).

The CHP configuration (180kWh/m²a natural gas) has fewer running costs and less total emissions than the condensing boiler (155kWh/m²a). Reason is the significantly reduced electricity demand and an additional 30kWh/m²a feed back to the grid. The CHP has a higher initial investment of approx. 50.000 € compared to 21.000 € for the boiler configuration.

Based on these numbers, the building owner was able to make a qualified decision. Future measurements at this building will be made to validate the results. These validations using measurement and test scenarios in comparison to other tools are an important part of current work.

FUTURE PROSPECTS

As for today, it is possible to simulate the energy flow in a building using different technical configurations. Based on the results the configuration can be optimized manually and validated afterwards. Basic energy management algorithms can be tested within the simulation. Energy usage and wastage are analyzable and comparable. Incorporation of modern charging concepts for e-Vehicles into the simulated building is also possible.

The future development aims to extend a database with simulation results and input-datasets, including different combinations of buildings, vehicles, locations and usages. The toolchain will also be linked to acknowledged tools for detailed component layout (i.e. PV calculation, heat demand). Furthermore the process of parameter variation and optimization of energy generation, usage, lifecycle cost and independence shall be automated.

Long term objectives are an independent system layout application and standards for assessment of local renewable energy systems.

ACKNOWLEDGEMENTS

The described tool is developed within the research project “Residence and Mobility”. The aim is to cover all energy demands of a family and their individual lifestyle with the renewable energy provided around the building they live in.

Fig. 9: test and reference building implementing in-house micro-wind-turbines, PV, CO_2-heat-pump and 12m³ heat storage and management system

Resulting technologies are to be applied to projects like hotels, office buildings and industrial sites. The research project is encouraged with subsidies from the European Union and Sächsische Aufbaubank.

NOMENCLATURE

p, f	… potential, flow
V, ρ, c_p	… volume, density, heat capacity
(Δ)T	… temperature (difference)
U, I, φ	… voltage, current, power factor
e	… current energy
Q, q	… heat, heat power
U	… building element parameter
g	… energy translucency
S	… radiation correction factor
L	… air change rate
$R_{\%}$	… energy recovery rate
w	… correction factor
v, r	… flow indices
med	… medium
amb	… ambient
trans	… transmission
sol	… solar
vent	… ventilation
vert	… vertical
nom, op	… nominal, operational
HT, HB	… Heating, heat bridge

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