Complex Large-Scale Heating, Cooling and Power Supply Models – Virtual Renewable Power Plant Simulation with Modelica

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Abstract

Today, continuously decreasing profit margins on energy selling as well as increasing prize volatility and restrictive legislation already force local utility companies to find extraordinary business concepts. Those solutions integrate combined heat, cold and power supply as well as sophisticated control algorithms to build virtual power plants including large-scale renewable energy production (e.g. photovoltaic power plants, biogas power plants, etc.) and local energy storage (large-scale battery storages, eMobility, etc.).

This way, simulation engineers have to focus on those new requirements by adapting existing building and energy supply simulation approaches to large-scale problems. This paper presents some interesting aspects of model-based virtual power plant controller design with an adapted Modelica framework.

Introduction

In each country in the world, buildings will always be very important energy consumers. Unlike many other consumers in mobility or industrial processes, a building complex requires several different energy forms, especially heating, cooling and electricity demand changes drastically over the year and within the day.

Increasing energy costs as well as strict legal regulations challenge architects as well as engineers to find sophisticated building energy supply solutions with maximum system efficiency. These solutions tend to become complex and building specific so the use of appropriate simulation tools is a basic engineering requirement.

One of those sophisticated energy solutions is grouping adjacent buildings to grids with combined heat, cold and power supply with district heating or cooling grids. This provides synergy effects between heat, cold and power production and enables optimized system configurations with maximum operation times and minimum system costs.

Like conventional building HVAC systems, combined heat, cold and power supply grids need suitable design processes. The better such a system is optimized the more the user specific energy consumption gains importance, e.g. better building insulation increases user-specific heat / hot water consumption share. Volatile renewable energy efficiency highly depends on condition-based storage behavior (e.g. solar thermal gains depending storage temperatures). Furthermore, planners need to consider frequently changing energy costs as well as sophisticated controller architecture. Altogether, good planning decisions require suitable numeric systems simulation models of buildings and HVAC components.

Today, there are two different types of energy simulation platforms available. On the one hand, there are very accurate and detailed building physics and component simulation models (e.g. Nandrad/Delphin - Paepcke et.al. (2016), EnergyPlus, Modelica Buildings library – Wetter (2009)) which enable detailed thermal and electrical analysis. HVAC system simulation platforms (e.g. TRNSYS – Perschk (2012)) provide models for sophisticated components feasibility and economic studies, but mainly focus on single buildings.

On the other hand, grid and power plant simulation models make it possible to evaluate and optimize power plants and their grid interaction (e.g. Modelica ClaRa library – Gottelt (2016)) or complete power grids in cities or rural areas (e.g. Modelica TransiEnt library – Andresen et.al. (2015)).

However, both simulation approaches hardly enable accurate simulation of coupled heat, cold and power grids including 100+ buildings with detailed heat, cold and power generators, storages and grid elements at the scale of a city quarter. In grid simulation, the models are not detailed enough to evaluate different system configurations and controller concepts. In building simulation, the detailed building physics models require 1000+ parameters, which lead to inacceptable calculation times. This way, different research groups worldwide already started to create new modelling and calculation platforms (e.g. Gianniou et.al. (2015), Berthou et.al. (2015)). Most of them provide smart approaches to improve the calculation of buildings' energy demand. Other toolsets improve grid modeling with easy-to-use component models (e.g. Giraud et.al. (2015)) or detailed databases (e.g. Fliegner et.al. (2016)).

New building simulation approaches are still needed which combine sufficiently accurate building physics simulation with fast and numerically stable grid simulation. Furthermore, those approaches must integrate multi-domain simulations of thermal and

electrical components with strongly differing time constants in one toolchain or better one tool.

The versatile modeling language Modelica again proves as an adequate tool. The new Green City library includes a wide range of large-scale energy supply and storage systems. Furthermore, simplified building models enable fast simulations of complete city quarters with several streets and buildings as well as individual connections to the grid. These models help to evaluate complex grid structures and supply systems.

Furthermore, these dynamic simulation models can be used for a model based controller design, to implement new grid control strategies and superior energy management systems. These algorithms help to use district heating grids as virtual electric storages for renewable energy surplus. This way, the grid models become essential parts of balancing energy controllers for local utility companies and energy traders.

Simulation Platform

Green City is a newly developed simulation library in ESI ITI's SimulationX for holistic modeling of heating, cooling and electric power supply, storage systems and consumption models in city quarter size. It is based on the existing Green Building approach used to simulate sophisticated HVAC systems including renewables, storages, control strategy and eMobility.

To cope with the new challenges for system engineers and local utility companies, Green City applies this widely used approach of HVAC and power system modeling to larger-scale problems. The basic model components design is similar because most considerable boundary conditions are comparable.

Power, heat and cold supply in buildings uses solar or wind energy, any kind of fuel and even superior supply grids for energy production. The building directly consumes that energy, internally distributes it between different equipment rooms or stores it in different forms of thermal medium or electric storage. Large-scale grids mainly show similar behavior.

For example, combined heat and power units simultaneously produce heat and power in buildings. Cogeneration plants in large-scale district heating and power grids are of equal importance. PV modules on top of a building have the same properties like large-scale photovoltaic power plants. On system scale even wind parks can be modelled with a specific windmill number and areal directional characteristics. Power and heat supply systems provide size-independent functionality. Relevant differences exist regarding components size (e.g. hub height of wind turbines), influences of scalability (e.g. wake effect in wind parks) as well as interfaces (e.g. single/three phase grid connection in buildings vs. low/medium/high voltage connection in local grids).

Storage tanks in buildings mainly show the same physical behavior like large-scale grid storages, e.g. hot water tanks compared to large-scale stratified heat storages. Even batteries of 2 kWh and 2 MWh mainly differ in the number and kind of battery cells since the different internal structure can be simplified when the focus is on system layout and interaction.

Furthermore, overall energy efficiency highly depends on transmission losses between energy supply and consumption. For heating grids these are mainly heat losses through pipe insulation, temperature losses in heat exchangers and pumping power while in electrical grids these are voltage drops in cables and transformation losses. All these physical effects are easily scalable.

To make modelling easier, the Green City Library adds new functionality for electrical grids like high and medium voltage AC as well as high voltage DC connectors with variable voltage levels, voltage propagation. These grids can be connected by additional transformers (AC/AC) or different AC/DC and DC/DC converters. The converters can be configured as ideal or with suitable assumptions regarding transfer losses.

Green City's major added value are simplified statistic building models representing local heat, cold and power consumption in different building types or even whole streets. These models automatically define hundreds of building physics parameters (e.g. wall thickness or insulation) via model-internal statistic data sets.

Simplified Building Models

Fast but still accurate building simulation in city quarter size requires simplified building simulation models. Green City offers two approaches for fast simulation.

One option is the 'Building Load' model. It integrates heat, cold and power consumption via pre-calculated load characteristics. The second option is a parametric building model. This model consists of a simple building structure with a reduced number of thermal zones as well as a reduced parameter set based on statistics (e.g. building age, insulation thickness, floor space, etc.).
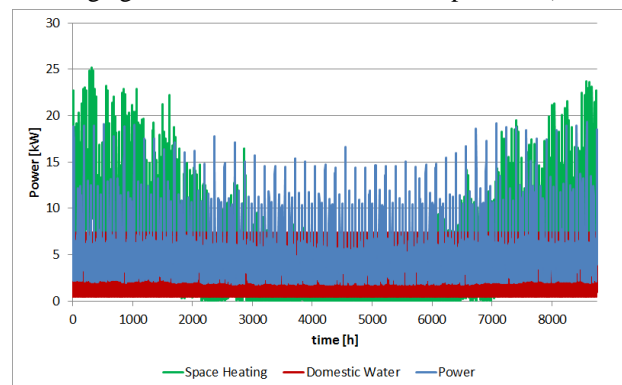

Figure 1: Sample input data of 'Building Load' model representing space heating, domestic water and power consumption

Figure 1 shows the characteristics of a sample modern office building based on 'Building Load' model. In the sample project, these characteristics of space heating, domestic water and power consumption were pre-calculated using EQUA's IDA ICE simulation tool.

To add those dynamic characteristics to a complex HVAC system model, 'Building Load' model internally
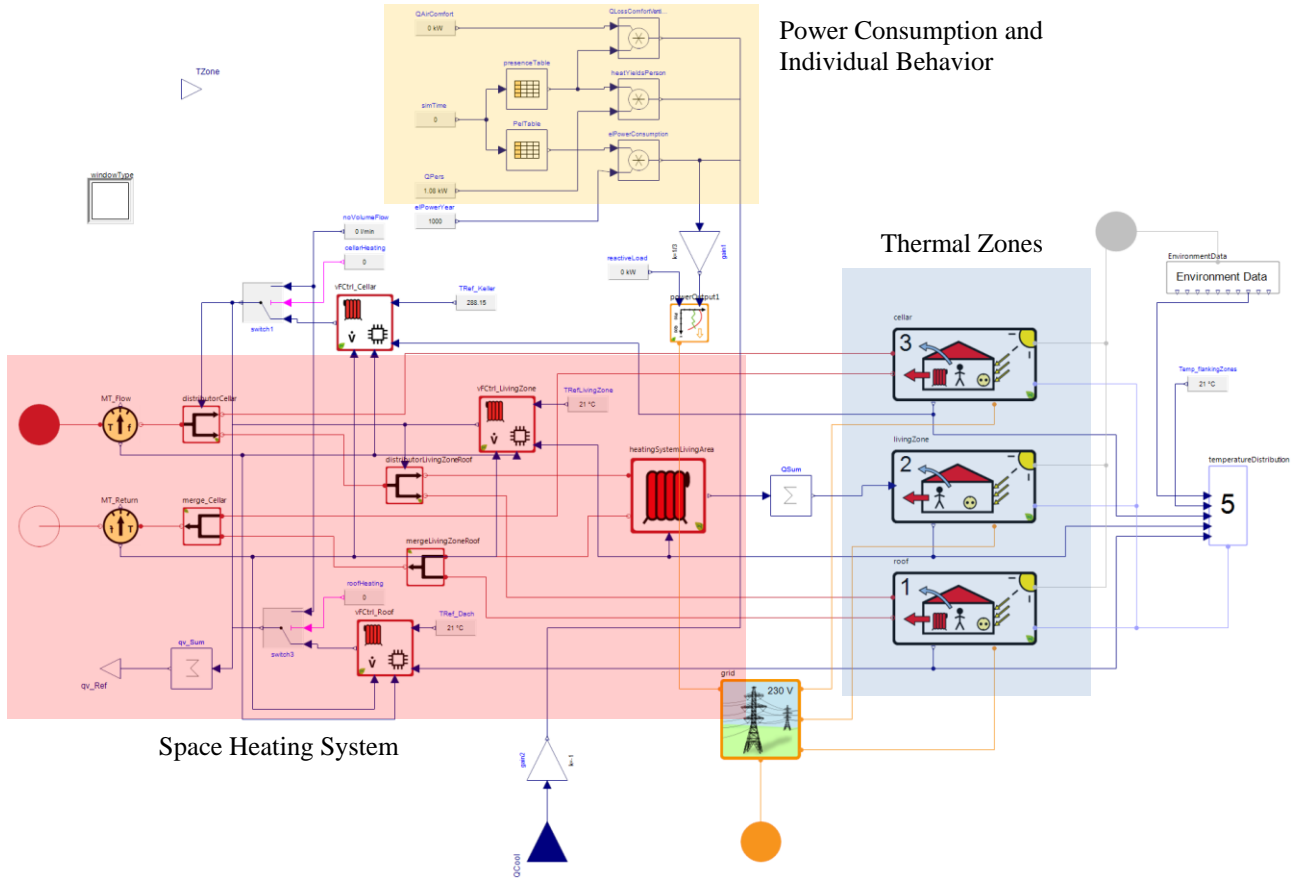
Figure 2: Green City 'Simple Building' model with three thermal zone, space heating and power consumption

calculates resulting heating system return temperature depending on available flow temperature as well as externally controlled volume flow.

$$c_p \cdot \rho \cdot V_{SH} \cdot \frac{d(T_F - T_R)}{dt} = Q_{Heat} - c_p \cdot \rho \cdot q_v \cdot (T_F - T_R) \quad (1)$$

This way, the model is an easy way to include highly accurate building physics data into a dynamic HVAC system simulation without the high impact on simulation performance.

With this approach, it is possible to simulate streets or even complete city quarters within adequate simulation times in an accurate way, especially in case of areas with many buildings of a comparable type and size (e.g. residential areas). It separates the actual HVAC system and grid from building physics simulation. The method separates a complex multi-physical simulation task (e.g. building physics, heating, cooling and power systems design and controller development) into consecutive engineering tasks. This way, building and energy system engineers with different professions as well as different simulation tools with different strengths can contribute to the identification of optimal system solutions.

However, this first simplification approach also has some disadvantages. Firstly, engineers need more than one simulation tool to simulate both building physics and HVAC system behavior, which corresponds to tooling costs and breaks in the workflow. Secondly, decoupled simulation models do not provide sufficient information about feedback effects (e.g. room temperature reductions in case of insufficient flow temperature availability). This is especially important for controller design, if new control algorithms use additional storage capacities with respect to personal comfort aspects, for example in accepting room temperature drops to effectively use predicted solar heat gains or avoid cooling.

For such tasks, Green City provides another simplified building physics simulation approach. Figure 2 shows the structure of the 'Simple Building' model including three thermal zones (i.e. basement, stories and attic), space heating and variable power consumption. Building physics in this model are represented by only three thermal zones to achieve minimum simulation time.

Comprehensive statistics define the remaining parameters for zone sizes and usage as well as wall, floor and ceiling structure. This model approach bases on an IWU research project (Loga et.al. 2005) which analyzed thousands of different existing buildings in Germany.

The IWU project results provide architects and engineers a validated data platform for the easy identification of existing residential buildings' energy demand. Few parameters, like building's geometry, heated floor space area, room height, number of stories and building define all required façade, floor, ceiling and window sizes. Energetic behavior mainly depends on specified building age and subsequent refurbishment measures, like

improvement of wall insulation (c.f. eq. (2)). Relevant parameters like transmission factors are also part of these statistics.

$$U_{insulation} = \frac{1}{\frac{1}{U_{wall}} + \frac{d_{insulation}}{0.04 \cdot \frac{W}{m^2 \cdot K}}} \qquad (2)$$

The 'Simple Building' model in Green City integrates this simple set of parameters as well as all parameter approximations based on those IWU research project statistics (c.f. Figure 2). Furthermore, 'Simple Building' model adds cooling system properties as well as further information about electricity consumption based on the standard load profiles used by local utility companies.
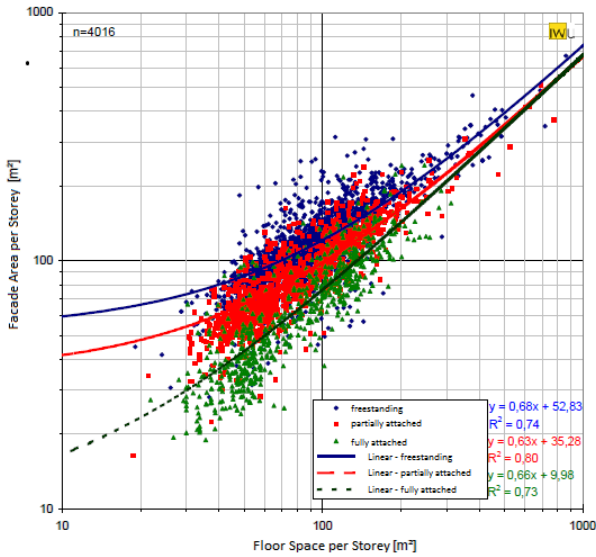

Figure 3: Sample results of IWU research project – façade areas vs. floor space areas regarding building attachments (Loga (2005))

However, the IWU research project only provides statistic data sets about residential buildings, built before 1994. To make the model more flexible, the 'Simple Building' model needs further characteristics of non-residential buildings. Research results of other research institutions (e.g. Franke et.al. (2016)) can therefore contribute to this approach as well by adding additional, for example country-specific building envelope parameter sets and databases.

Besides extended building physics-specific parameters, those required additional data sets mainly refer to power consumption characteristics based on alternative industry standard load profiles as well as additional data sets describing the energetic behavior of new structures, built after 1995. Therefore, model integrated statistic data sets add maximum U-Values of different construction parts (e.g. walls, ceilings, roof, etc.) defined by latest legislations (e.g. German Energy Saving Act 2002 to 2016).

Combined Heat and Power Grid Models

This paper describes a new concept of combined simulation of thermal and electric grids as a part of building energy supply infrastructure.

Figure 5 therefore shows a simple Green City example including a street with two office buildings as well as one single-family house, one row house and one dwelling house. Heat supply infrastructure includes a 100 kW cogeneration plant and a 500 kW peak-power boiler. A 10m3 heat storage provides hydraulic decoupling of volatile heat consumption and production. In the electric part a transformer connects low voltage grid and medium voltage grid of the local utility company with several other power consumers and local renewable power production, e.g. a wind park with about 2 MW nominal power output.

This simple model enables the engineer to identify the right size of cogeneration plant, peak-power boiler and heat storage regarding district heating grid's overall heat demand, a quite simple engineering task. However, local utility and energy supply companies as well as energy traders today face bigger challenges. They need suitable storage and control solutions for the increasing renewable energy surplus in the power grid.
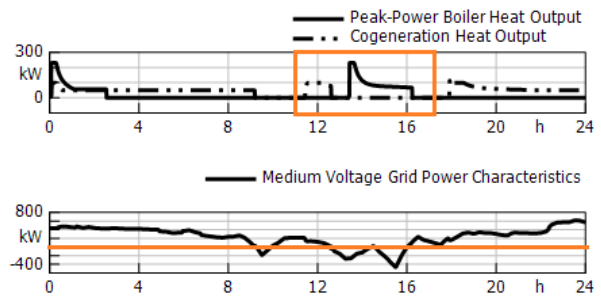

Figure 4: Simulated heat output of cogeneration plant and peak-power boiler with respect to grid power characteristics

Coupling district heating grid's large storage capacities can help to provide additional capacities and corresponding balancing energy in the future. This requires sophisticated prediction of heat and power consumption in the grid. New controllers therefore can include adequate model functionality during the design process (i.e. software-in-the-loop) or these models can become a part of the controller itself as independent prediction units.

Figure 4 exemplarily shows how renewable power availability can affect cogeneration plant operation in future coupled grids. The implemented simple controller avoids cogeneration power supply when renewable power surplus is available (i.e. wind park). In case of still existing heat demand, peak-power boiler takes the place of the primary cogeneration plant.

Complex Virtual Power Plant Models

One single district heating grid with an integrated cogeneration plant has minor impact on overall required storage capacities. However, a so-called 'virtual power plant' consisting of a high number of such system configurations is one major opportunity for a future well-balanced power grid infrastructure.
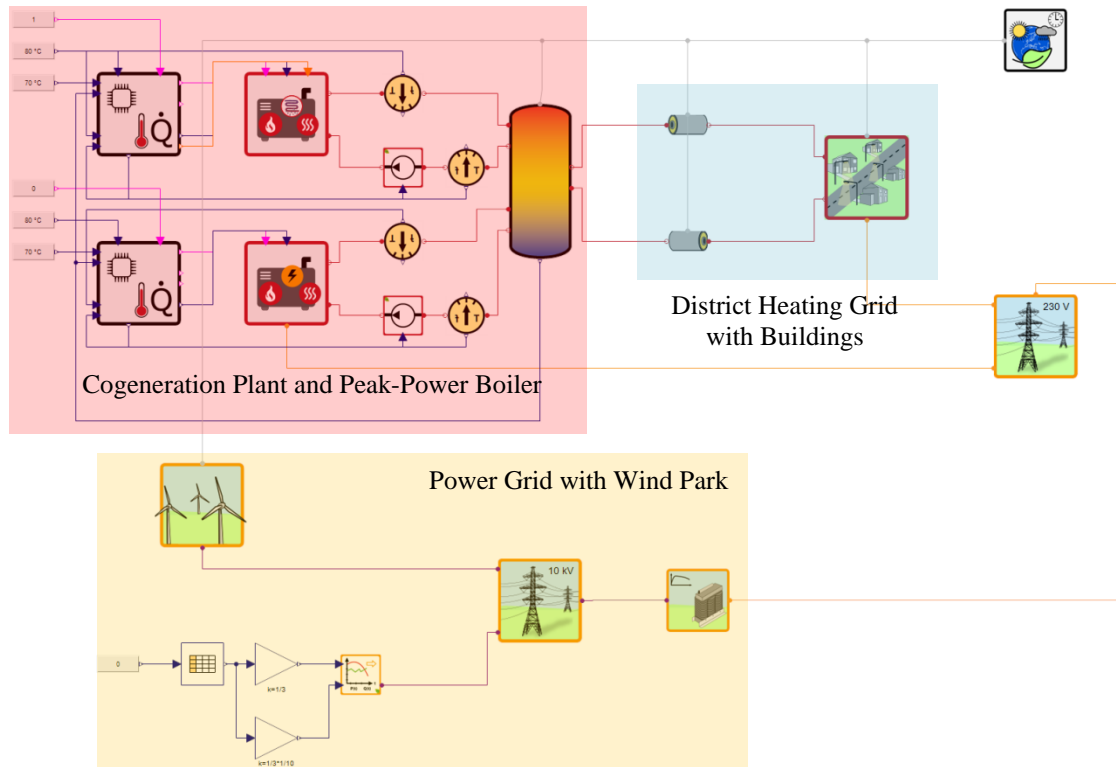
Figure 5: Simple district heating grid model with connection to local medium-voltage power grid

Such an infrastructure requires suitable controller and energy management functionality. Their design needs highly accurate but still fast simulation models, especially if those district heating grids include an increasing number of volatile renewables as well as local storages. Figure 7 this way shows one sophisticated district heating grid example.

This grid example is a role model for future highly efficient district heating grids with high renewable energy share. The considered district heating grid provides heat to 100+ single-family-homes and dwelling houses of highest energetic standard (i.e. German Energy Saving Act Version 2016). To minimize heat losses with respect to overall system costs, grid temperature is at a minimum level of 25 °C during summer. Prototype heat pump systems including both operating modes compressor and heat exchanger provide domestic hot water in each connected building even at this low grid temperature level. Minimum compressor operation times furthermore reduce extra power consumption.

The cogeneration plant supplies main heat amounts. Again, the superior grid controller only enables heat and power production when no renewable power surplus is available in the grid (i.e. positive balancing energy). A large-scale solar thermal plant mainly provides additional heat amounts during transient times and summer. A hydraulically decoupled heat pump completes this sophisticated system concept. While it further cools down grid return temperature, it increases solar thermal efficiency. However, the heat pump only runs in times of low renewable power production, e.g. by photovoltaic power plants and wind parks.

Finally, each building heat pump provides further negative balancing power because superior grid controller also regards the available thermal storage capacities of the individual buildings.
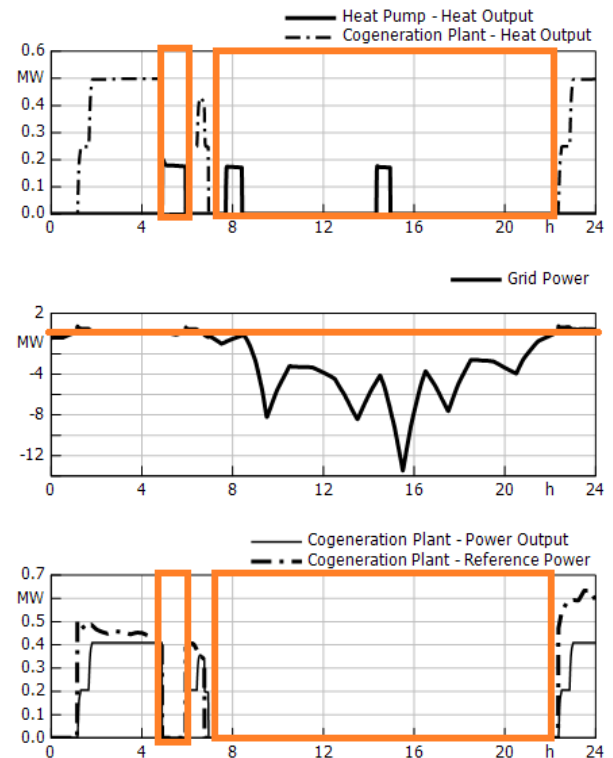

Figure 6: Simulated heat output of heat pump and cogeneration plant as well as cogeneration power control with respect to grid power characteristics
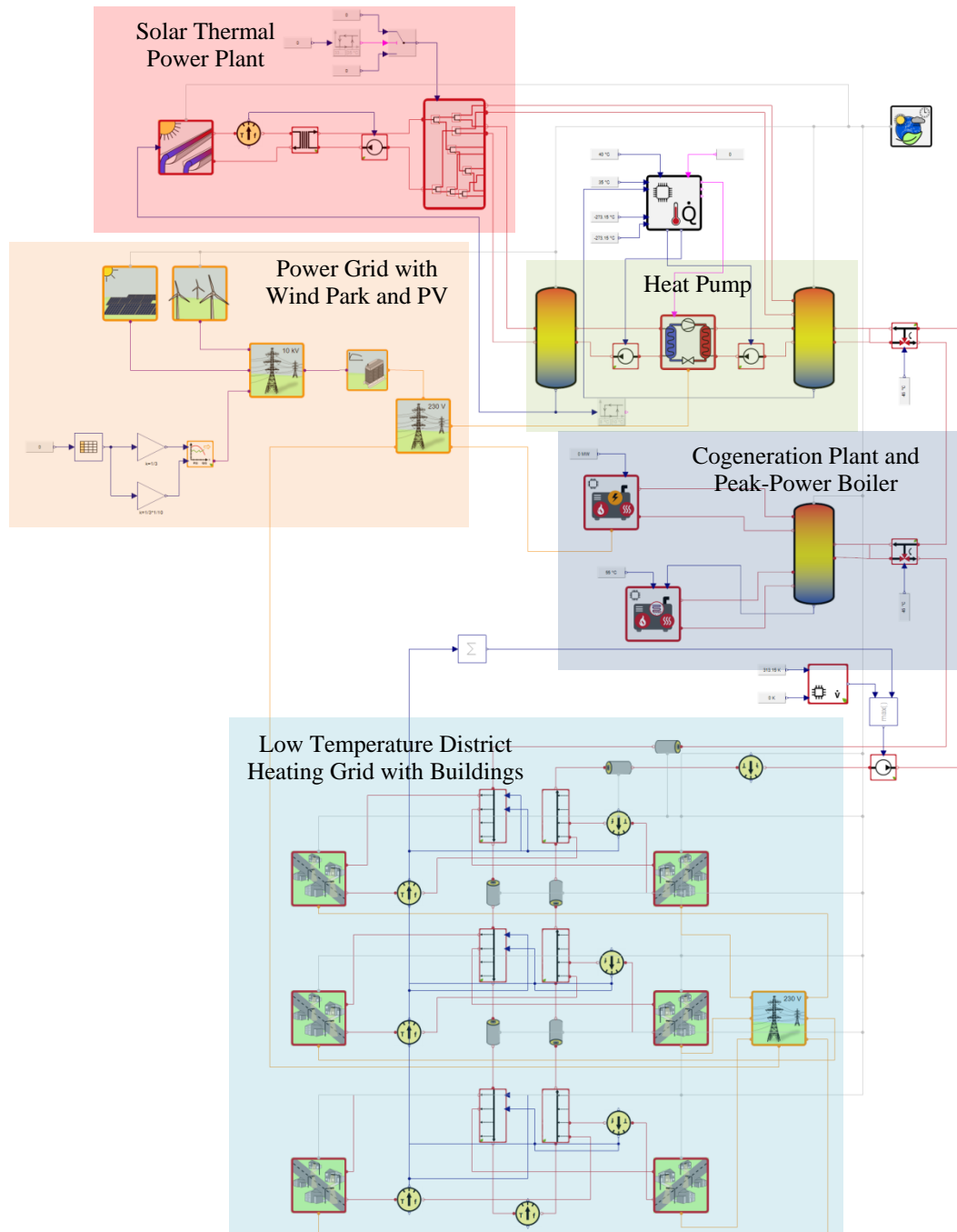
Figure 7: Complex renewable district heating grid with large-scale solar thermal power plant as well as positive and negative balancing energy via cogeneration plant and large-scale heat pumps

Figure 7 shows a more complex district heating grid than shown in Figure 5. This structure includes several system components that can provide balancing energy to the power grid, both positive (i.e. power production) or negative (i.e. power consumption). therefore shows some interesting simulation results for one specific reference day regarding heat pump, cogeneration plant and grid power behavior.

This grid integrates high renewable energy production by a 5 MWp photovoltaic power plant and a wind park with 16 windmills with a nominal power of 2.35 MWp each. This way, simulated grid power mostly remains under 0 MW level, i.e. local utility company must sell much energy to the transmission grid operator for this reference day (windy summer day).

During times of renewable energy surplus, the superior grid controller enables heat pump operation, i.e. district heating grid will store surplus energy as heat if corresponding heat and cold storage temperature is within suitable limits.

The cogeneration plant only will run if renewable power production is lower than power consumption and connected district heating grid requires heat. Furthermore, the superior grid controller controls heat

and power output of cogeneration plant depending on its reference, i.e. superior grid controller works as cogeneration power controller.

Virtual Power Plant Controllers

Single heating systems in a district heating grid, e.g. cogeneration plant (positive balancing energy) or heat pumps (negative balancing energy) can only provide a limited share of balancing energy.

A so-called solar thermal heat pump can compensate renewable energy surplus if storage temperatures are within suitable limits. For the presented complex district heating grid structure, simulation results (c.f. Figure 8) show that heat pump size is limited to 50 to 100 kW heat output. A maximum annual operation time of less than 500 h per year is not acceptable regarding required investment costs.
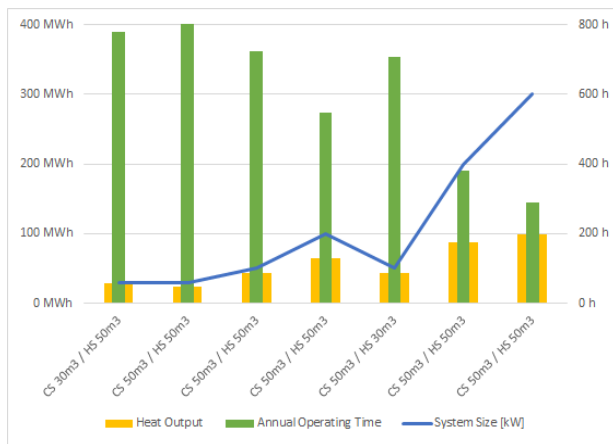

Figure 8: Comparison of simulation results regarding suitable solar thermal heat pump size

Furthermore, renewable energy production can exceed grid's power consumption up to 5 to 7 times because future grids will require high renewable energy share even during unsuitable weather conditions (e.g. winter nights with low wind speed). This way, future district heating grid concepts need additional solutions to provide sufficient balancing energy.

The presented low temperature grid approach therefore shows additional advantages. There are about 100+ decentral heat pumps with about 3 to 10 kW electric power consumption each inside the 100+ connected buildings. The buildings' thermal heat capacity is much higher than available storage capacities in the electric grid. Those individual heat capacities are included in Green City's 'Simple Building' model as well (i.e. Building weight based on German DIN 4108 standard).

- Light: < 50 Wh/(m^{2}K)
- Medium: $> 50 / < 150$ Wh/(m^{2}K)
- Heavy: > 150 Wh/(m^{2}K)

The complex district heating grid model in Figure 7 can thus simulate deviations of the nominal indoor temperature depending on input data set of space heating consumption as well as heat input by district heating grid. Furthermore, the superior grid controller can shift individual decentral heat pump power (Q_{HP}) depending

on this reference value difference (T_{Build}-T_{Ref}) as well as existing electric grid requirements.

$$C_{Build} \cdot \frac{d(T_{Build} - T_{Ref})}{dt} = Q_{HP} - Q_{Consumption} \quad (3)$$

The individual heat pump's impact on the district heating grid ($Q_{DistrictHeating}$) as well as the electric grid (P_{el}) furthermore depends on its individual *COP* (coefficient of performance) for space heating and domestic water consumption.

$$Q_{DistrictHeating} = \frac{COP}{COP+1} \cdot Q_{HP} \quad (4)$$

$$P_{el} = \frac{Q_{HP}}{COP} \quad (5)$$

This additional model component functionality enables model-in-the-loop tests of superior grid controller strategies. Furthermore, these model components can become part of a sophisticated controller architecture integrating models for model-based power consumption prediction. Therefore, the new Functional Mockup Interface (FMI) standard helps to export such Modelica models as standalone calculation units, the Functional Mockup Units (c.f. Wicke et. al. 2014).

Conclusion

The new Modelica-based Green City library enables the engineer to model simple and complex heat, cold and power grids in city quarter size with acceptable simulation performance and accuracy.

Since the developed district heating grid models mainly use pre-simulated heat and power consumption profiles of specialized building physics simulation tools (like IDA ICE or EnergyPlus, etc.), the resultant accuracy of each modeled building in the grid is quite good, normally within +/- 10 to 20% deviation to later measurements. However, today user behavior represents greater influence on building's energy consumption. For example, heat consumption share of domestic water supply is increased because of improved energetic building standards. Model accuracy thus further deviates if user behavior is less predictable.

In case of a statistically high number of considered buildings (e.g. in city quarter or larger) the importance of reduced predictability decreases because of statistical effects. Then, even less accurate building models, for example simplified building models (e.g. Petrushevski et.al. (2015)) can provide suitable input data sets for the desired grid simulation.

Main goal of the presented approach is to provide fast simulation models for large-scale heating, cooling and power supply system evaluation. The presented simulation models (c.f. Figure 7) usually need about 15 to 60 minutes for a one-year simulation. Besides the actual simulation time, engineers always focus on required modeling time as well. Such a quite complex district heating grid model with around 200 to 300 parameters needs around one to two days to be finally set up.

Green City includes new opportunities to simulate thermal and electrical building behavior for a large

number of buildings in one model together with sophisticated heat, cold and power supply systems and control strategies.

Engineers can now use these models to implement complex control strategies for coupled grid architectures with respect to maximum energy efficiency and reliability as well as acceptable system costs. The presented Green City approach thus extends the scope of building-related multi-criteria optimization methods (e.g. Schwan et.al. (2015)).

Furthermore, the development of future predictive control algorithms in grids, for example for virtual power plants, requires such new modeling approaches to enable a suitable energy demand prediction for both heating and cooling as well as power production (e.g. Liu et.al. (2015), Runvik et.al. (2015)).

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Nomenclature

C_p	= Specific heat capacity
ρ	= Density
V_{SH}	= Heating medium volume
T_F	= Flow temperature
T_R	= Return temperature
q_v	= Volume flow
Q_{Heat}	= Heat consumption
$U_{insulation}$	= U-value of insulated wall
U_{Wall}	= U-value of wall
$d_{insulation}$	= Thickness of insulation
Q_{HP}	= Heat power output of heat pump
T_{Build}	= Building indoor temperature
T_{Ref}	= Reference temperature
C_{Build}	= Building heat capacity
$Q_{Consumption}$	= Building heat consumption
$Q_{DistrictHeating}$	= District heating grid heat supply
P_{el}	= Power consumption of heat pump
COP	= Coefficient of Performance