Proceedings of BS2013:
13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28

SIMULATION OF ENERGY CONSERVATION MEASURES AND ITS IMPLICATIONS ON A COMBINED HEAT AND POWER DISTRICT HEATING SYSTEM: A CASE STUDY

Mehmet Elci[1], Sattaya Narmsara, Florian Kagerer and Sebastian Herkel

Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany
[1]Phone: +49 761 4588 5582, E-Mail: mehmet.elci@ise.fraunhofer.de

ABSTRACT

In this study a methodology for simulating large-scale energy systems is described. In particular the simulation of a district, supplied by a combined heat and power district heating system is the analysed energy system.

In the methodology firstly, the districts' space heating demand is modelled with the use of a simplified dynamic building model, developed in Modelica. Secondly, the districts' domestic hot water demand is modelled by using the measured data and generating an average standard profile. Thirdly, the heat distribution is simulated by a simplified dynamic district heating network model, developed in Modelica. Finally, the CHP system-, boiler- and thermal storage-models are implemented in the statistical modelling environment *GNU R* as static models. These static models are used to calculate the operation of the heating systems by utilizing the simulated total heating demand as input, which are obtained by the above mentioned models.

The methodology is presented by means of a case study. In this case study, a scenario is calculated, in which firstly, the change of a district's heating demand profile due to energy conservation measures in buildings is explored. Subsequently, the implications of this demand modification on the supply side of the district heating system are investigated.

It is shown, that the methodology developed in this study is appropriate, in order to investigate large-scale energy systems with similar boundary conditions as the presented case study.

Additionally, due to the simulation results of the investigated scenario, it is shown how the refurbishment of a district has significant implications on a district's combined heat and power district heating system.

INTRODUCTION AND MOTIVATION

In the field of energy research, the investigation of energy systems on a large-scale level is addressed. One reason for this can be the purpose to study the interaction of medium-scale sub-systems. While complex and detailed simulations often carry out the investigation of individual small-scale systems, this approach is often not appropriate for large-scale systems. The quantity of sub-systems in larger systems needs to apply a different approach. Otherwise firstly, the modelling process would be too costly and secondly, the simulation would be computationally too expensive. Therefore, simplified modelling approaches are required, which produce simulation results that are accurate enough for the purpose of the study. Numbers of urban energy modelling have been developed. Some aim to optimize system configurations of energy systems within a single frame-work. For instance, *CitySim* consolidate different models in a single simulation tool (Robinson et al., 2009). Others follow a modular modelling approach (Fuchs et al., 2012; Huber and Nytsch-Geusen, 2011).

There are many research questions, which require large-scale simulation approaches. One particular example that is investigated in this Paper as a case study, is the following:

Refurbishment of the existing inefficient building stock will be one of the top priorities, due to its high potential in savings. However, there may be conflicts between energy conservation measures in buildings supplied by district heating systems and the operation of the district heating systems. District heating systems are more efficient and more economic with higher load densities (IEA, 2008). Hence, efficiency measures in large building stocks could have major implications on the load density (Rosa et al., 2009). Some researchers in the energy field claim, that utilities always feared this outcome, and therefore never had a real interest in encouraging energy efficiency measures (Palm, 2006). However, in the years ahead, energy conservation measures will be one of the major instruments of Germany's energy transition and consequently inevitable. Utilities are therefore interested in research in this field, in order to find out the best possible solution.

In this Paper, a methodology to model and simulate a large-scale energy system is described. This is shown by means of a case study. In this case study, a district's change of heating demand profile due to energy conservation measures and its implications on the district heating system is investigated.

METHODOLOGY

In this section the methodology to simulate the case study is described, which is a large-scale energy system consisting of a demand side and a supply side. On the demand side the space heating demand and the domestic hot water (DHW) demand is modelled. On the supply side the heat distribution and the heat generation is modelled. The modelling approaches have to be simplified compared to many other modelling approaches. The applied tools are *Modelica*, *Dymola*, *QGIS* and *GNU R*.

At this point, it must be mentioned that the methodology described in this study is only adaptable for systems with a similar structure and with a similar data basis. For instance, the described method for DHW modelling requires measured data of total heating demand. If these data are not available, a modification of the method is necessary.

Data of the buildings are provided by the local housing association. Information about the district heating networks' characteristics and topology is provided by the local utility in form of Geographical Information System (GIS) data. The local utility also delivered measured data of the districts' total heating demand for a period of one year.

The methodology's workflow and tool chain is shown in Figure 1.

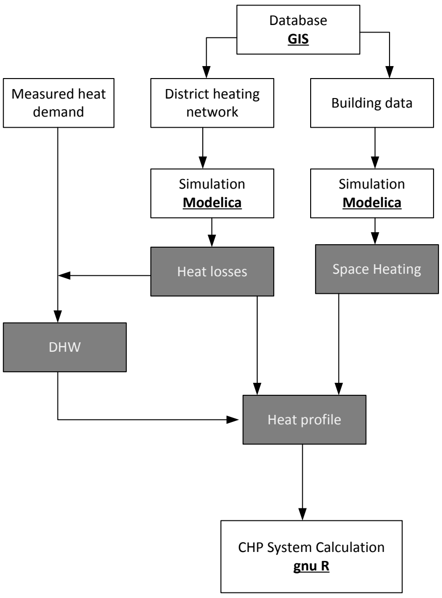

Figure 1 Workflow and tool-chain of the described methodology.

Due to the fact that the methodology is presented using a particular case study, firstly, the case study is introduced. This gives an overview of the system and thus, makes the subsequent described modelling approach clearer.

Case study

Weingarten is a district in Freiburg/Germany with about 10,000 inhabitants and was built in the 1960s. However, in this study not the entire district of Weingarten is investigated. In order to facilitate the modelling process, only the area of Weingarten-West and -South is considered for this study. It is assumed that the results for entire Weingarten can be obtained by extrapolating from the results of the area of Weingarten-West and -South.

The investigated energy system includes the demand side as well as the supply side. In the simulated scenario, the buildings of the investigated area are refurbished regarding their energy performance. The area of the case study is highlighted in Figure 2.

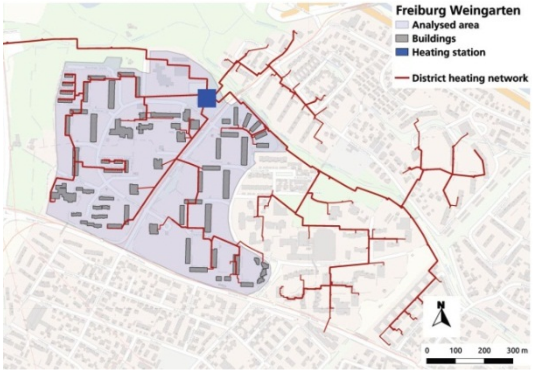

Figure 2 Map of the case study Weingarten in Freiburg, Germany

Demand side

There are 45 buildings in Weingarten-West and -South. 22 buildings are connected to the district heating *circuit West* and 23 to the district heating *circuit South* (see Figure 2). There are different building types, 4 and 8-storey multifamily houses, 16-storey tower blocks, terraced houses and also non-residential buildings (grocery stores, a school and a community centre) for instance. Most of the buildings were built at the same time and have approximately the same building envelope characteristics. Hence, they have the same poor energy performance. The main data of these buildings is shown as average values of all buildings in Table 1.

Table 1
Main data of all buildings (average values)

PARAMETER	VALUE	UNIT
conditioned floor area	3782	m
area to volume ratio	0.51	m /m
thermal envelope area	4146	m
mean U-value	0.86	W/(m K)

The majority of the buildings belong to the local housing association who intends to refurbish the Weingarten district in order to create a more sustainable area.

In the refurbishment scenario investigated in this paper, the conservation measure applied is an envelope retrofit. The retrofit standard is based on the requirements described in the *German Energy*

Savings Ordinance (EnEV, 2009). Table 2 displays the buildings' envelope parameters before (average values) and after the refurbishment (based on EnEV).

Table 2
The buildings' envelope parameters before (average values) and after the refurbishment (based on EnEV)

PARAMETER	BEFORE	AFTER	UNIT
U-value external wall	0.81	0.28	W/(m K)
U-value windows	2.61	1.3	W/(m K)
U-value bottom plate	0.41	0.35	W/(m K)
U-value roof	0.29	0.2	W/(m K)

Supply side

Two gas fired CHPs with 3.14 MW thermal capacity and three gas fired boilers, each with 9 MW thermal capacity and a 360 m^3 thermal storage, provide heat to the district Weingarten and its neighbouring district Rieselfeld with an overall network length of 16.35 km. The *circuit West* and *circuit South*, which distribute heat to Weingarten-West and -South have a total network length of 4.5 km.

The above mentioned heat generation and storage systems supply heat to the entire district. However, in this study only Weingarten-West and -South is considered, as described in subsection *Case study*. Therefore, also the supply side has to be scaled down in the same ratio as the demand side. Because the total heating demand of Weingarten-West and -South is about 30%, also the heat generation and storage systems are assumed to have only 30% of their actual capacity. Thus, the obtained overall system (demand side and supply side) is representative for the entire district heating area.

Modelling

In the following four subsections, the modelling approach is described. Firstly, the space heating demand is modelled by a simplified dynamic building model developed in Modelica. Secondly, the DHW demand is modelled by using the measured data of total heating demand and generating an average standard profile. Thirdly, heat distribution is modelled by a simplified dynamic district heating network model also developed in Modelica. Finally the heat generation and storage technologies are modelled in GNU R

Space heating demand

In order to calculate the space heating demand of the buildings a dynamic building model is utilized. This building model is developed in Modelica using the modelling and simulation environment Dymola.

The building model is based on the so called *Thermodynamic model* (an equivalent circuit model) described in the German standard (VDI 6020-1, 2001) and (VDI 6007-1, 2007). However, it is partly simplified. For instance, long wave radiation exchanges between interior and at external building components are neglected. Short wave radiation exchanges with the internal non-transparent and at external building components, are also not considered.

Figure 3 shows the equivalent circuit model of the building model. The opaque components, which are exposed to an asymmetric heat load (exterior walls, roof and bottom plate), are represented by three resistors and two capacitors. The components, which are exposed to a symmetric heat load (internal walls and ceilings), are represented by only one resistor and one capacitor. The parameters for resistors and capacitors are calculated according to (VDI 6007-1, 2007).

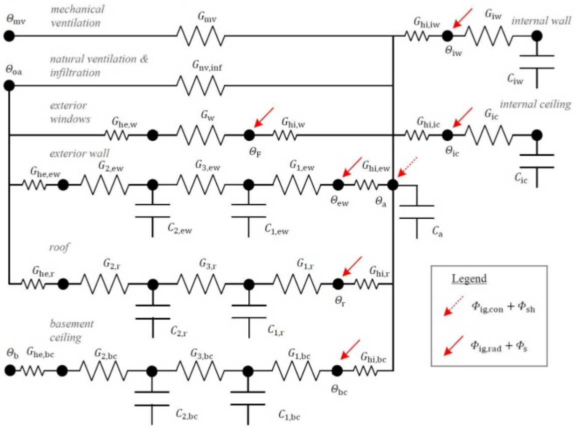

Figure 3 Equivalent circuit of the Modelica building model.

The implementation in Modelica is carried out mainly using the Modelica Standard Library 3.1. If a required model is not available in the standard library, own models are developed or existing models are modified. Figure 4 shows the graphical representation of the Modelica building model. By going one more level down in a sub-model, for instance the external wall (circled in green in Figure 4), the resistors-capacitors-structure can be identified (see Figure 5).

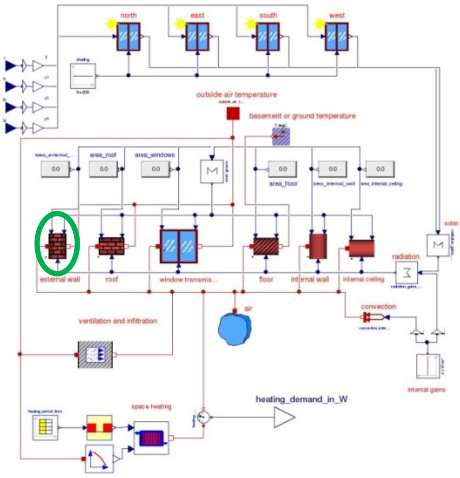

Figure 4 Graphical representation of the Modelica building model.

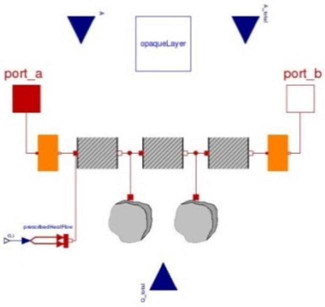

Figure 5 Graphical representation of an external wall model.

The process of modelling the buildings of the district is not only facilitated by utilizing a simplified building model, but also by clustering the buildings which are connected to the same circuit and have identical structural properties to determined types. Hence, 27 building types are obtained (17 on South and 10 on West) by clustering the original 45 buildings. These buildings are then simulated in order to obtain the total space heating demand of Weingarten-West and -South before the refurbishment.

For the calculation of the space heating demand after the refurbishment, the model parameters described in Table 2 are adjusted.

Domestic hot water demand

Several methods to generate DHW profiles have been developed. For instance, a method which considers statistical means for user activities generate draw-offs profiles throughout the year (Jordan and Vajen, 2005). However the method is limited to single buildings. A sub task of IEA SHC Task 44 tried to generate standard daily profile with a variation of the energy demand over the year (Haller et al., 2012). In a subtask of ECBCS Annex 42 average daily profiles of several countries (Knight et al., 2007) have been developed. In this paper a method is developed for generating DHW profiles based on available, measured data of a short period.

In order to obtain the DHW demand of the buildings the measured data of the summer period of the district heating system is taken as a basis. It is assumed that the measured heating demand of the district heating system in summer does not contain space heating demand. Thus, after deducting the distribution losses of the network (see subsection *Heat distribution*) from the measured demand in summer, the remaining heating demand in summer is considered as solely DHW demand. In a second step this DHW profile is utilized in order to form a standard-profile for all days of the week. This is carried out by using the heat profile during the summer period from the first Monday of June to the last Sunday of September (see Figure 6).

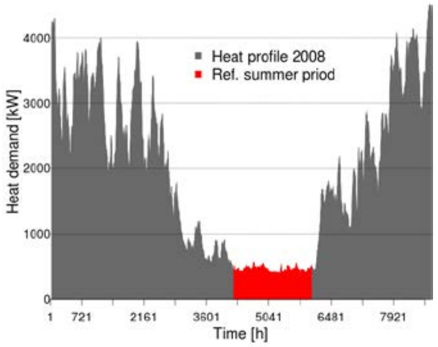

Figure 6 Reference summer period which is being used to generate typical weekly DHW profile

Afterwards the hourly average of each week day from Monday to Sunday within this period is calculated. Thus, the results can be considered as typical DHW. Subsequently this reference profile is extrapolated over the entire year. Certainly, damped oscillation in form of a sine curve of the heat profile for DHW over the year must be considered. This is necessary due to seasonal change of fresh water temperature throughout the year.

Heat distribution

Heat distribution losses are a significant share of the total heat production of the district heating system. In order to calculate this share, the heat distribution by the network is simulated.

Several thermo-hydraulic models have already been implemented in order to be applicable to answer relevant energetic problems at district level (Nytsch-Geusen, 2009). In Modelica specification 3.1 a common interface for fluid based components is introduced by the Modelica organization (Casella et al., 2009). The released standard library contains models that are implemented to provide flexible use for e.g. a dynamic pipe. However, this dynamic pipe model is in this case too complex. Modification and extension based on Modelica Standard Library 3.1 has been done in order to simplify the modelling of pipes with different characteristics for instance insulation, installation depth etc.

The purpose was to build a base district heating pipe model that can be generated semi-automatically by reading the GIS data. The code structure of Modelica is very suitable for this purpose. Nevertheless, to reduce the complexity in order to improve simulation runtime is still a problem. Thus, parts of the district heating network are aggregated to solve this problem. The resulting inaccuracy is acceptable for this case study. To keep the calculation as simple as possible neighbouring buildings were aggregated to consumer blocks.

The open source GIS tool Quantum GIS (QGis) and the communication interface, which is based on Python is used. An export plugin of QGis was developed to generate desired network segments as a

Modelica code. Certainly, each pipe could have been connected automatically from the plugin. This automatization is not essential because the pipes still have to be graphically adjusted in the GUI of Dymola.

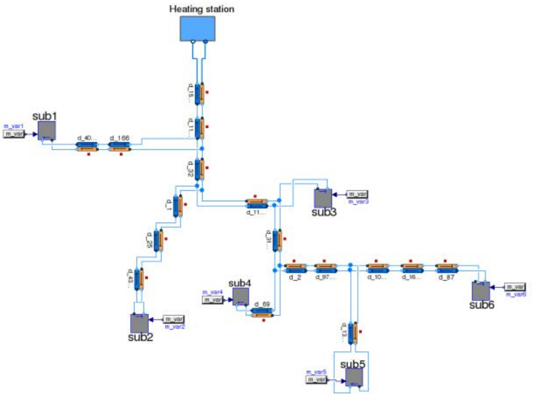

Figure 7 District heating model of the circuit South in Weingarten Freiburg.

During the modelling process the structure and spatial relation of the network is tried to be maintained. Only the neighbouring pipes with same diameter and insulation are aggregated in order to reduce the complexity.

An important factor for heat loss is the temperature surrounding the pipe. For the first approximation pre calculated ground temperature by the KASUDA model (Kasuda and Archenbach, 1965) is used. This model calculates ground temperature at predefined depth depending on air temperature and thermal property of the ground. Figure 8 shows simulation result that contains absolute distribution heat losses and relative heat losses of circuit *South* in the case study.

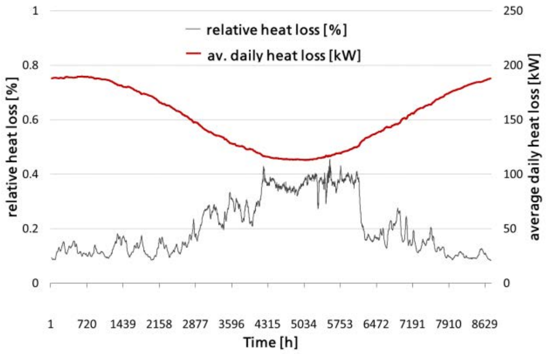

Figure 8 Simulated absolute heat losses and relative heat losses of circuit South of the case study

Heat generation

Heat generation with CHPs and Boiler including thermal storage is simulated with *GNU R* (CRAN, 1999). Predetermined profile of total heat demand serves as input for the simulation. The simulation is performed with fixed time steps to improve the performance. In this way, the simulation provides results very fast. Two control algorithms of the thermal units are available within the simulation. Either a simply decision algorithm could perform the allocation of heat production or it can be done by economical optimization at every single time step. With both algorithms, the simulation needs to ensure the energy supply security. This paper briefly describes the linear optimization implemented in the simulation. The target of the optimization is to minimize the overall generation cost. Equation (1) shows the objective function:

$$\min \sum cost_{\text{prod.}} = cost_{\text{prod,boiler}} + cost_{\text{prod,CHP}} + cost_{\text{prod,storage}} \quad (1)$$

Solving linear equation is carried out with an *lp_solve* interface for *GNU R*. Figure 9 shows annual simulation results for heat generation of the case study.

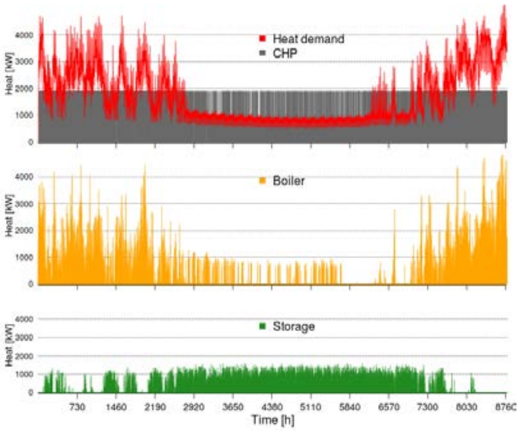

Figure 9 Simulation result of heat generation.

DISCUSSION AND RESULT ANALYSIS

In subsections *Model evaluation* and *Scenario simulation*, the results of this study are presented and discussed. The first subsection contains the evaluation of the modelling approach and the second subsection the results of the case study simulation (refurbishment scenario).

Model evaluation

Space heating demand

The building model is validated by comparing the results of a simulation with the results of a validated building model of IDA ICE (Sahlin et al., 2004; Achermann and Zweifel, 2003). This cross-validation is carried out by determining a reference building (a 4-storey multi-family house in Freiburg/Germany) and simulating the building with both models for a one-year period.

It is assumed that in the summer period, no heating demand is required. The summer period is defined as the period from 15th May to 14th September. For this period, no set-point temperatures are defined in the models. For the simulation the *TRY* data of region 12 from the German Meteorological Service (DWD, 2013) is utilized.

Figure 10 shows the results of this simulation. The upper diagram displays the entire year and the diagrams below two example weeks. In addition to the visual evaluation, the discrepancies are also quantified. The summer period is not considered in the numerical evaluation. Table 3 shows the results. The coefficient of determination indicates that generally the simulation results are in good agreement. By the mean bias error, which is close to zero, it can be seen that there is no systematic error (no general under- or overestimation). However, the root mean square error, which is 10.68 kW (mean value of the IDA ICE results is 46.24 kW), shows that there is a clear discrepancy between the two models. The comparison of the root mean square error with the mean bias error indicates that the models oscillate differently. By a visual examination of the graphs, it is revealed that the curve of the Modelica simulation is flatter. The IDA ICE results contain larger load swings. Nonetheless, for the purpose of this study, which is simulating the space heating demand of an entire district, the simplified building model can be considered as sufficient.

Table 3
Quantification of simulation result deviations. Mean value of the IDA ICE results is 46.24 kW (reference value).

MEASURE	VALUE	UNIT
Coefficient of determination	0.89	-
Mean bias error	-0.11	kW
Root mean square error	10.68	kW

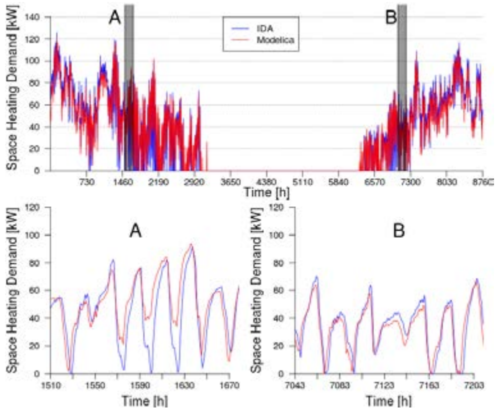

Figure 10 Results of the IDA ICE simulation and Modelica simulation. The upper diagram represents an entire year. The lower diagrams represent an example week respectively.

<u>Total heating demand</u>

The simulated total heating demand is obtained by assembling the simulated space heating demand, the developed DHW profile and the simulated distribution losses. Figure 11 shows the assembled total heating demand.

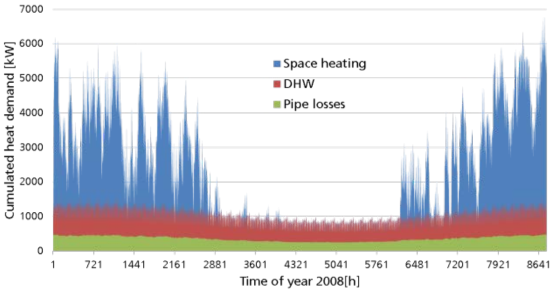

Figure 11 Generated heat profile for area of case study.

The simulation method is evaluated by comparing the simulated total heating demand with the measured total heating demand. In Figure 12 it can be seen that the model underestimates the heating demand in the periods of lower demand and overestimates in the periods of higher demand. This shows that there is a potential to improve the modelling process. The coefficient of determination, which is 0.86, confirms this potential. However, due to the higher uncertainties, large-scale models perform generally worse than small-scale models. For the purpose of this case study, the model performance can be considered as sufficient.

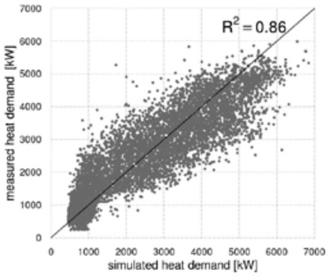

Figure 12 Comparison simulated result with measured data.

Scenario simulation

In this subsection, the implications of the refurbishment on the district heating system are discussed. Figure 13 demonstrates the variation in total heating demand before and after the refurbishment scenario. It can be seen, that the conservation measures have a significant effect. This effect is stronger in the periods in which the heating demand is the highest. Thus, the entire heat demand of the district is flattened. The overall reduction of the heating demand is about 30%.

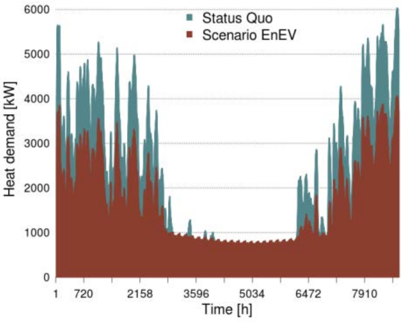

Figure 13 Heat demand profile before and after refurbishment scenario.

In Figure 13 the change in CHP operation regime due to the reduction of heat demand is shown. It can be seen that the operation regime of the second CHP unit is significantly reduced, compared to the operating regime before the refurbishment. Thus, the average runtime of the CHP units decreases by 10% (see Table 4). However, because the energy conservation measures affect in particular the higher load demands, the heat production from the gas boilers is far more affected than from the CHP units. As a consequence the ratio of CHP heat production to boiler heat production increases from 59% to 75% (see Table 4). Thus, the overall efficiency of the district heating system increases too. The use of the thermal storage is represented by the part of the CHPs that are above the heat load duration curve. The primary energy factor of the heat generation, calculated according to (DIN V 18599), as well as the operating times of the CHPs is shown in Table 4.

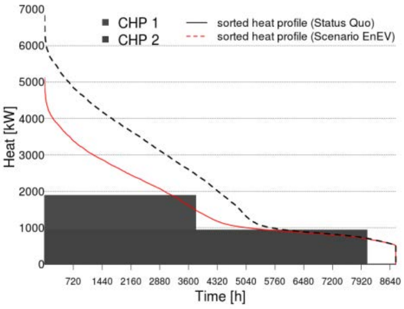

Figure 14 Simulation results of heat generation compared with heat demand of Status Quo and refurbishment scenario.

Table 4
Simulation results

CASE	PRIMARY ENERGY FACTOR	CHP RATIO	AVERAGE RUNTIME
Status Quo	0.63	59 %	6494 h
EnEV	0.40	75 %	5920 h

Nonetheless, with lower heat demand the heat distribution losses become relatively more important, which can be seen in Figure 15. The lower the heating demand becomes, the lower becomes the linear heat density. The linear heat density is defined as the annual heating demand, divided by the length of the distribution network. The increase of the relative distribution losses increases the negative effect on the economics of the district heating system.

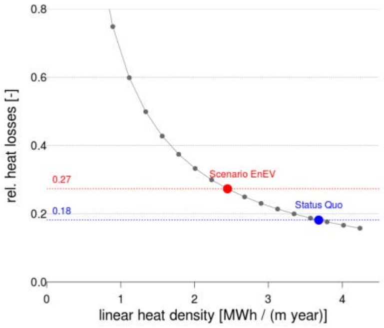

Figure 15 Linear heat density vs. relative heat losses.

The results of the case study described above, indicate that the economics of a district heating system after a refurbishment should be improved. This can be achieved by adapting the system to the new circumstances.

CONCLUSION

This study has shown that the methodology developed in this study in order to investigate large-scale energy systems, has proven to be suitable. However, if there were a poorer data basis of the district, additional methods would have been required. Hence, methods in order to estimate for instance the characteristics of a district's buildings could be necessary in these cases. The approach of utilizing simplified models has proven to be useful, despite the discrepancies, which were discovered in the evaluation of the models. This study has also shown that the refurbishment of a district can have significant implications on a district's combined heat and power district heating system. The implementation of an envelope retrofit led to a decrease of space heating demand. This effect was relatively stronger the higher the heating demand was. Thus, the entire heat demand of the district was flattened. This flattening had significant consequences.

Firstly, the average operating hours of the CHP units decreased by 10%. However, the diminishing effect on the boiler was even stronger. Hence, the ratio of CHP heat production to boiler heat production in fact increased. Because CHPs are the more efficient technology, the overall efficiency of the district heating system increased (primary energy factor decreased from 0.63 to 0.40). Thus, the implications of the refurbishment are ecologically advantageous, because less energy is required in general and additionally the district heating system becomes more efficient. However, from en economic point of view, the refurbishment of the district can have significant disadvantageous for the utilities. This is due to less sales of heat, while the supply systems with higher capacities were already invested in. Secondly, the heat distribution losses became more important relative to the situation before the refurbishment. This increases the negative effect on the economics of the district heating system. Recommendations for future research are firstly, further development of the methodology regarding the improvements discussed above. Secondly, solution methods in order to counteract the negative implications of the refurbishment process on the district heating system should be investigated.

ACKNOWLEDGEMENT

This work is a summary of many projects. They were founded by the German Federal Ministry of Economics and Technology (BMWi 0327400O and 0327400P) and the European Commision within the project “E-Hub”.

NOMENCLATURE

$cost_{\mathrm{prod.}}$ = overall energy generation costs

$cost_{\mathrm{prod,boiler}}$ = operational costs of boiler

$cost_{\mathrm{prod,CHP}}$ = operational costs of CHP

$cost_{\mathrm{prod,storage}}$ = operational costs of thermal storage

REFERENCES

Achermann M. and Zweifel G. 2003. Praxisnahe Validierung von Simulationsprogrammen, Luzern, Switzerland.

CRAN, 1999.The Comprehensive R Network, http://cran.r–project.org.

Dalla Rosa, A., and Christensen, J.E. 2011. Low-energy District Heating in Energy-efficient Building Areas. Energy 36 (12) (November): 6890–6899. doi:10.1016/j.energy.2011.10.001.

DIN V 18599 Vornorm, 2007.German Institute for Standardisation. Energetische Bewertung von Gebäuden – Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung.

DWD: German Meteorological Service.2013. Testreferenzjahre von Deutschland für mittlere und extreme Witterungsverhältnisse. Available at: http://www.dwd.de/TRY (Accessed 14th February 2013)

EnEV. German energy saving ordinance, Verordnung zur Änderung der Energieeinsparverordnung; 2009.

Fuchs, M., Lauster, M., Teichmann, J. and Müller, D. 2012. Modularer Modellansatz zur Simulation Von Energiesystemen Auf Quartiersebene. In IBPSA Conference BauSim. Berlin.

Haller, M.Y., Dott, R., Ruschenburg, J., Ochs, F. and Bony, J. 2012. The Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38 Part A: General Simulation Boundary Conditions.

Huber, J., and Nytsch-Geusen, C. 2011. Development of Modeling and Simulation Strategies for Large-scale Urban Districts. In Building Simulation, 14–16. Sydney.

IEA SHC Task 44:Haller, Michel Y, Ralf Dott, Fabian Ochs, and Jacques Bony. 2012. The Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38 Part A: General Simulation Boundary Conditions.

Jordan, U., and Vajen, K. 2005. Program to Generate Domestic Hot Water Profiles with Statistical Means for User Defined Conditions. In ISES Solar World Congress.

Kasuda, T. and Achenbach, P. 1965. Earth temperature and thermal diffusivity at selected stations in the United States. ASHRAE Transactions 71(1), 61–75.

Knight, I., Kreutzer, N., Manning, M., Swinton, M. and Ribberink., H. 2007. ECBCS Annex 42 Subtask A: European and Canadian non-HVAC Electric and DHW Load Profiles for Use in Simulating the Performance of Residential Cogeneration Systems. Ed. Ian Knight and Hajo Ribberink.

Nytsch-Geusen, C. Ljubijankic. M. and Unger. S. 2009. Modelling of Complex Thermal Energy Supply Systems Based on the Modelica-Library FluidFlow.

Robinson, D., Haldi, F., Kämpf, J., Leroux, P., Perez, D., Rasheed, A. and Wilke, U. 2009. CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning Solar Energy: 1083–1090.

Sahlin, P., Eriksson, L., Grozman, P., Johnsson, H., Shapovalov, A. and Vuolle, M. 2004.Whole-building simulation with symbolic DAE equations and general purpose solvers. In Building and Environment 39, 2004, 949-958.

Verein Deutscher Ingenieure.2007. Directive 6007-1: Calculation of transient thermal response of rooms and buildings - Modelling of rooms, Düsseldorf, Germany.

Verein Deutscher Ingenieure. 2001. Directive 6020-1:Requirements on methods of calculation to thermal and energy simulation of buildings and plants - buildings, Düsseldorf, Germany.