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# A Modelica based computational model for evaluating a renewable district heating system

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## 1. ABSTRACT

District heating (DH) systems are considered a viable method for mitigating long-term climate change effects, through reduction of CO<sub>2</sub> emissions, their high conversion efficiencies and their ability to be integrated with renewable energy sources (RES). The current evolution towards sustainable DH, e.g. integration of RES, results in increased complexity and diversity during the early-design phase.

In the early-design phase of DH systems a feasibility study is conducted to assess if the economic and environmental factors of the project meet the given requirements. This assessment is generally conducted with traditional district heating computational models (DHCM), utilizing a simulation language which limits the evaluation of sustainable DH systems in terms of flexibility and comprehensibility. The need for an alternative language capable of effectively modeling DH systems with integrated RES led to the use of Modelica, which offers improved flexibility, reusability as well as hierarchical and multi-domain modeling. This paper presents a case study, for the evaluation of a new DHCM analyzing its modeling capabilities and system performance, of an educational campus formed by eight institutional buildings connected to a centralized power plant, holding among others a biomass gasifier and a gas boiler. For an optimum utilization of the biomass gasifier, two power plant configurations are assessed: a biomass gasifier system with and without thermal energy storage (TES).

The system performance evaluation indicates a significant increase in the utilization of the biomass gasifier with 8.2% (353 hours) compared to results obtained from the traditional DHCM. This deviation is due to a more accurate consideration of the DH thermal capacity and the space heating demand. Furthermore, the models in this DHCM enable assessments of the impact of building retrofits or climate change scenarios. Thus, the increased modeling capabilities and system performance demonstrate that this new DHCM is suitable and beneficial for early-design feasibility studies of innovative RES integrated DH systems.

**Keywords:** Renewable Energy, District Heating Systems, Simulation Modelica & Dymola

## 2. INTRODUCTION

The building sector is responsible for approximately 34% of global primary energy demand, of which 75% is used for thermal purposes (IIASA, 2012). DH systems currently provide 12% of the building thermal demand in the European Union alone. Integrated with power plants, combined heat and power units or industrial waste-heat sources, these DH systems have proved in the last decades to be capable of reducing the use of primary energy (European Commission, 2012; IIASA, 2012).

Through the first three DH generations, the techniques evolved towards lower distribution temperatures, material lean components and prefabricated equipment. The latest or 4th generation of DH systems, which is currently under research, is able to further decrease grid losses, supply renewable DH and be an integrated part of smart grid systems (e.g. supply and demand controlled systems) (Lund et al., 2014). Energy services companies, like Cofely Netherlands, aim to introduce these 4<sup>th</sup> generation DH systems applying sustainable energy sources and/or smart grid features.

At the early-design phase of DH systems, the feasibility of multiple system configurations are evaluated both economically and technically. The assessment of these system configurations is generally performed with a DHCM developed for traditional DH systems. This traditional DHCM restricts the assessment of new developments (e.g. integration of RES) due to the lack of flexibility and inability to resolve the complexity of such systems. These restrictions make feasibility studies, using a traditional DHCM, a challenging and labor intensive task, with an unreliable output.

This paper presents and discusses the development and evaluation of a DHCM. The use of Modelica as simulation language provides a modeling environment with a natural representation, increases the reusability of models and components, grants higher flexibility in system configuration as well as facilitates hierarchic and multi-domain modeling, enabling assessments of combined thermal, electrical and control related problems. These aspects are key for early-design phase assessments of multiple DH configurations, contributing to a more reliable and detailed final design.

The suitability of this new DHCM for early-design phase feasibility studies is analyzed through the re-evaluation of a renewable DH system for an educational campus. This case-study considers a DH system connecting 8 institutional buildings to a state of the art biomass gasifier, enabling the generation of renewable heat and electricity from locally collected residue of wood cuttings. Two configurations are considered for the case study, respectively a power plant with or without a stratified thermal storage system in an attempt to increase the gasifier utilization.

### **3. METHODOLOGY**

The methodology for the development and evaluation of the new DHCM is presented in this section. In subsection 3.1, *Building performance simulation*, the motivation for using building performance simulation is emphasized and the choice for Modelica as a modeling and simulation language will be discussed. In subsection 3.2, *Case study*, the technical aspect of the case study will be described since the subsequent section is presented according to the case study specifics. In subsection 3.3, *Computational model*, the approach taken for the development of the DHCM is presented following the components: heat generation, heat distribution, heat consumers and thermal energy storage.

#### **3.1 Building performance simulation**

Computational building performance simulation aims to provide an approximate solution of a realistic model in the real world (Hensen & Lamberts, 2012). The development towards the integration of RES in DH systems, with their intermittent behavior, or smart grid features, adds increased complexity to the current computational models. These models typically lack, among other things, modularity, multi-domain capabilities, realistic control behavior and flexibility for the users (Wetter, 2011). These shortcomings do not benefit users who seek a way to quickly assess, among others, innovative system designs or operation strategies.

To determine the platform for the development of a new DHCM a functional comparison is conducted (Table 1, Table 2) between, Dymola (Modelica), TRNSYS and Matlab Simulink. The comparison indicates that Dymola (Modelica) performs better in terms of modularity, multi-domain modeling, realistic control behavior and flexibility. Modelica is a freely-available, equation-based object-oriented language that is designed for component-oriented multi-domain modeling of dynamic systems. The equation-based feature permits acausal modeling, thus without considering computational order (Musić & Zupančič, 2006), which makes the reuse of classes easier and reduces faults compared to assignment-based modeling (e.g. TRNSYS, Matlab Simulink). Object-oriented modeling facilitates encapsulation which allows both reuse of components and evolution of models (e.g. referring to existing scripts). Multi-domain modeling enables modeling of combined disciplines such as electrical, thermodynamics, fluid dynamics and controls systems.

Furthermore, reusability makes it easy to use models and components, for example, from the Buildings library used in this study and developed by the Lawrence Berkeley National Laboratory (Wetter, 2010). The LBNL Buildings library is a freely available, open-source library with currently over 200 components and systems models for modeling building energy and control systems (Wetter, Zuo, Nouidui, & Pang, 2013). These features and available libraries make Modelica suitable for computational applications with high complexity requiring high performance simulation (Fritzson, 2010).

Table 1: Functional comparison simulation environments, part I

<i>Functional comparison simulation environments</i>				
	<b>Properties</b>	<b>Dymola</b>	<b>Simulink (Matlab)</b>	<b>TRNSYS</b>
<b>General</b>	Programming language	Modelica	M-code	Fortran
	Developer	Dassault Systemes	Mathworks	University of Wisconsin
	Software costs Academic	+	++	+
	Software costs Commercial	<b>0</b>	++	+
	Simulation time	<b>0</b>	+	+
Development time	++	<b>0</b>	+	
<b>Handling</b>	Scripting editor	+	++	+
	Graphical editor	++	<b>0</b>	+
	Symbolic manipulation	++	<b>0</b>	<b>0</b>
	Hierarchic modeling	++	+	<b>0</b>
	Reusability of models	++	<b>0</b>	+
	Post processing capabilities	<b>0</b>	++	<b>0</b>
	Model documentation	++	+	+
	Software documentation	+	++	++
Natural representation	++	<b>0</b>	<b>0</b>	
<b>Library</b>	Ease of use	++	+	+
	Open and editable libraries	++	+	<b>0</b>
	Validated libraries	+	++	++

Table 2: Functional comparison simulation environments, part II

<i>Functional comparison simulation environments</i>				
	<b>Properties</b>	<b>Dymola</b>	<b>Simulink (Matlab)</b>	<b>TRNSYS</b>
<b>Library domains</b>	Mechanics	++	+	-
	Controls	+	++	++
	Thermodynamics	+	+	++
	Hydraulics	++	+	++
	Electronics	+	++	+
	Buildings	+	<b>0</b>	++
<b>Simulation</b>	Continuous time systems	++	++	++
	Discrete time systems	++	++	++
	Debugging facilities	+	+	++
	Diagn. and sim. event logging	+	+	+
	Coupling features (FMI)	++	++	++
	Errors Description	+	<b>0</b>	++
<b>Specific</b>	Model calibration	+	++	+
	Design optimization	+	++	+
	Model management	++	+	++
	Code and Model export	++	++	<b>0</b>

### 3.2 Case study

In 2013, Cofely conducted a feasibility study during a tender for the transformation of an existing educational campus into a renewable educational campus. The tender required a proposal that would be able to reduce energy related CO<sub>2</sub> by 80% and provide long term cost reduction as well as added value for education. To satisfy these requirements Cofely designed and evaluated a combination of RES (e.g. solar PV and wind energy) and a DH system connecting the 8 institutional buildings with a centralized power plant (Figure 1). The power plant would use locally harvested biomass in a state of the art gasifier to convert it to syngas. The production of this syngas enables, by means of a combined heat and power unit, generation of renewable heat as well as electricity.

Two power plant configurations were considered during the evaluation: with and without a TES system. The development and integration of the biomass gasifier and the TES, as part of the traditional DHCM, was a time consuming and complicated process which led to uncertainties in the system performance and restricted optimization of the DH design. In the end, none of these configurations achieved the performance requirements that would ensure the economic viability of the design. A new DHCM with increased modeling capabilities will result in a more efficient system design and performance evaluation. Thus, the DH system and the two configurations will be re-evaluated with a new developed DHCM and compared with results obtained from the traditional DHCM.



Figure 1: Artist impression renewable campus

### 3.3 Computational model

The methodology for the development of the four essential DH aspects is presented and described in this section. Firstly, *heat generation*, which contains the biomass gasifier, peak installation and an emergency chiller integrated in the power plant model. Secondly, *heat distribution*, supply and return pipelines that circulate the heat carrying fluid (i.e. hot water) and enable the consumer to extract heat to satisfy its space heating demand. Thirdly, *heat demand*, where each of the 8 institutional buildings and their characteristic space heating demands are represented by a thermal energy model. And fourthly, *thermal energy storage*, a hot water stratified TES system to store or use heat originated from the biomass gasifier to increase its utilization factor. The four components combined form the DHCM (Figure 2) according to the specifics of the case study. The four components and their underlying models are designed to be able to be reused for other types of DH system configurations.

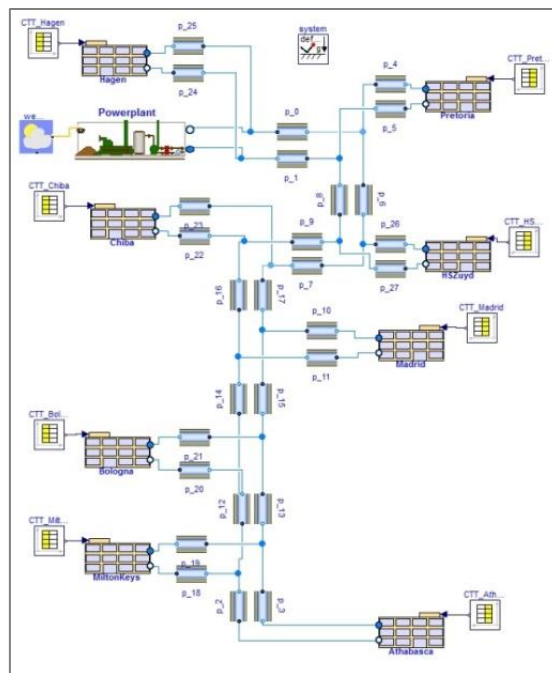


Figure 2: Top level of DH

### 3.3.1 Heat generation

The heat generation side (Figure 3) is represented by two closed loops, each of them connected by a heat exchanger to the distribution network. Both loops consist of a thermal energy source, respectively a gas boiler and a biomass gasifier, based on an existing boiler model.

The top loop containing the model of the gas boiler ensures the right supply temperature in the distribution systems (i.e. during peak demand) and operates as backup in case the biomass gasifier is shut down. The bottom loop contains the model of the biomass gasifier and its controller which is modeled to resemble the operation of a real gasifier. Furthermore an emergency chiller is connected to the gasifier loop to prevent the system from overheating since the gasifier has a slow response time to demand fluctuations.

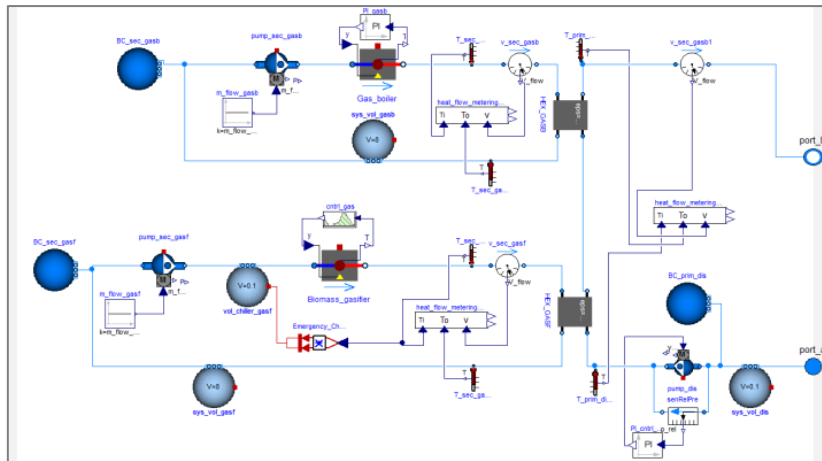


Figure 3: Model view, power plant without TES

The control strategy is designed to prioritize RES based heat generation, i.e. biomass gasifier over the gas boiler. The controllable models (e.g. heat sources and pumps) are connected to controllers specifically designed and tuned for the intended behavior of the models. The gas boiler is controlled by a standard PID, while the gasifier is controlled by multiple conditional statements, loops and timers since the operational behavior of the biomass gasifier is very distinctive compared to conventional heating sources. To illustrate this behavior, Table 3 indicates the specifications and a figure illustrating the slow reactivity of the gasifier to a random heat demand profile.

Table 3: Operation specification biomass gasifier (left) and its illustrating figure (right)

Operation specifications gasifier	
Maximum thermal output	720 kW <sub>th</sub>
Minimum thermal output	180 kW <sub>th</sub>
Thermal power rate	180 kW <sub>th</sub> / hr.
Shutdown delay period	8 hours
Shutdown period	12 hours
Start-up period	8 hours

Furthermore, for the pumps two types of controllers are present: a constant flow controller for the heat source loops and a differential pressure controller for the distribution loop. For the latter the actual flow control is provided by the adjustable valves present at the institutional buildings (Frederiksen & Werner, 2013).

### 3.3.2 Heat distribution

The distribution network is modeled as a two-way, supply and return, buried piping system enabling the transport of the heat carrying fluid. The distance covered by this network is about 560 meters with various pipe diameters according to the capacity required by the end-users. The piping network is modeled by connecting piping models (Figure 4), each of them accounting for friction and thermal losses, for uninterrupted sections of the network.

The friction losses, due to the fluid interaction with the piping inner wall, will result in a pressure drop that is accounted for by the distribution pump. The electrical energy required by the distribution pump will be dissipated as heat to the heat carrying fluid. The thermal losses, from the heat carrying fluid, through the insulated piping wall, to the ambient environment, can require a large share of the total heat production for a DH system (Elci, Narmsara, Kagerer, & Herkel, 2013). To increase the accuracy, the thermal losses are calculated as a function of the soil temperature using the Kusuda model (Kusuda & Achenbach, 1965). This model calculates the soil temperature at the desired depth, time and soil properties. The influence of various depths over soil temperature is illustrated in Figure 5. A constant depth of 1 meter for the piping network is considered for this case study.

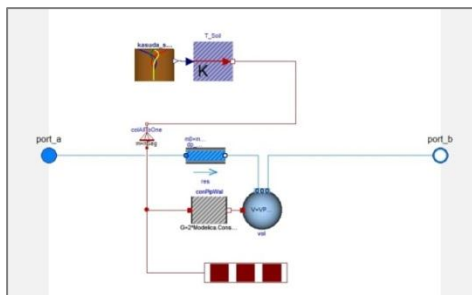


Figure 4: Modified pipe model

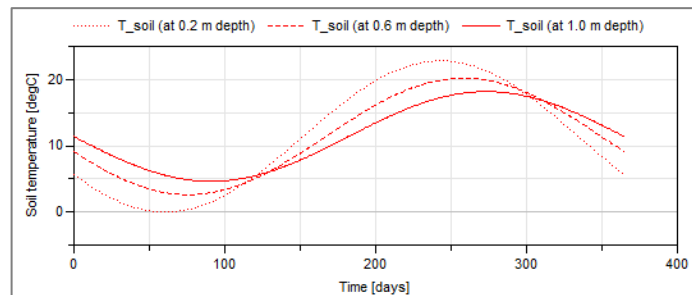


Figure 5: Temperature soil at various depths

### 3.3.3 Heat demand

This section presents the development, validation and calibration of a thermal building model accounting for the space heating demand of the institutional buildings. The demand caused by domestic hot water use is, in this case study, negligible and is therefore not considered.

#### 3.3.3.1 Structure of the building model

The building model, extracting heat from the distribution network to satisfy the space heating demand, consists of a building and a distribution loop (Figure 6). The building loop (right), connected to the distribution loop (left) by means of a heat exchanger, is designed to resemble the operational behavior of a radiator heating system consisting of thermostatic radiator valves. This is achieved by using a distribution pump, which flow is regulated by a PID controller to deliver a fluid return temperature according to a set point. Furthermore, a heat metering device is implemented to be able to monitor the space heating demand by considering the flow temperatures and volume flow. The distribution loop, a direct extension of the distribution network, has a controllable valve on the supply line, which controls the fluid flow to satisfy the supply temperature in the building loop and enables a minimal flow to keep a minimum supply temperature at the distribution side to reduce the startup delay.



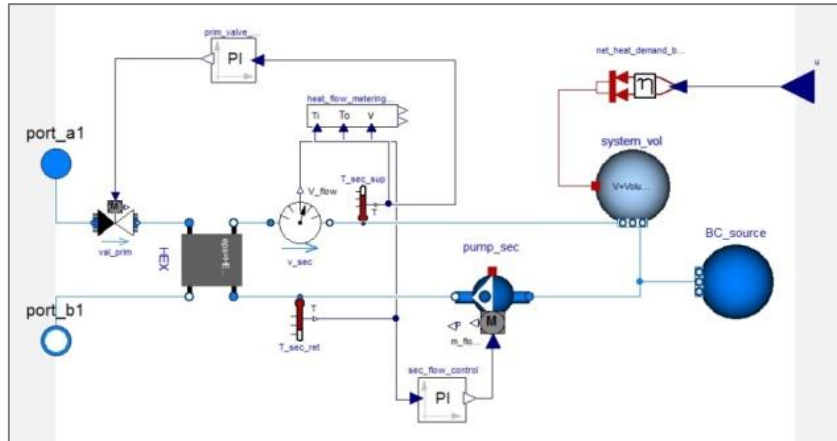


Figure 6: Model view, building model

Thermal energy is extracted from the building loop according to a space heating demand profile, with an hourly time step, that is connected to the model. The demand profiles for each building are computed using a thermal network model, as opposed to scaling demand profiles of buildings nearly identical to the institutional buildings, the method used by the traditional DHCM. Some benefits gained from using a thermal network model are that differences in building characteristics and the impact of climate change or retrofitting of the space heating demand can now be considered. The impact of climate change and retrofitting is not taken into account in this research, but it would be advisable for feasibility studies, since long term agreements are typical and retrofitting can have a large impact on the economics of a DH system (Elci et al., 2013).

The computation of the space heating demand profiles is performed with a thermal network model. This is an efficient way to keep the simulation time within a practical limit. Therefore, thermal network models are used widely for DH computational studies (Fuchs, Dixius, et al., 2013; Elci et al., 2013; Fuchs, Teichmann, Streblow, & Müller, 2013). The ISO 13790 simplified hourly model (ISO, 2005) calculates the space heating demand of the institutional buildings in this case study. This ISO model has been adopted for research (Van Dijk, Spiekman, & De Wilde, 2005; Kokogiannakis, 2007) and has been shown to yield satisfactory results when compared to similar second order thermal network models such as VDI 6007 (Lauster, Teichmann, Fuchs, Streblow, & Mueller, 2014).

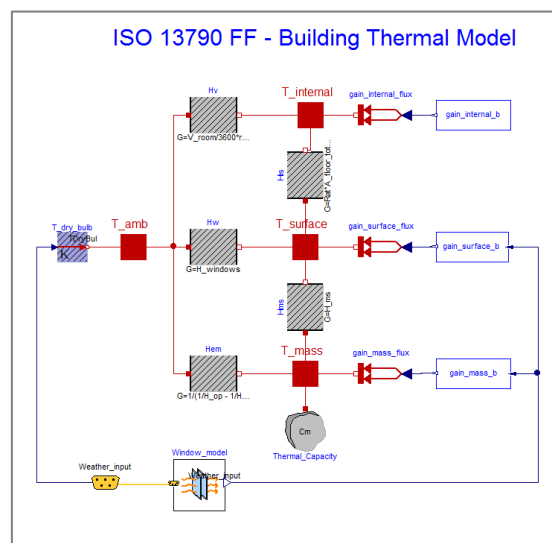


Figure 7: ISO 13790 FF thermal network

The ISO thermal network model is based on a 5 resistances and 1 capacitance electrical circuit model (Figure 7). Each of the resistances compute a heat flow from a building component (e.g. external wall, window, ventilation) while the capacitance accounts for the thermal inertia of the buildings thermal mass (i.e. walls, floors, ceilings). Furthermore, gains by solar radiation (diffuse and direct radiation) and internal heat sources (e.g. lighting, ICT) are considered by adding heat flows on the correct nodes, which can represent the surface, mass, ambient or internal air temperature.

### ***3.3.3.2 Validation and calibration of thermal network model***

The first validation of the thermal network model, conducted by simulating the BESTEST 600 case (Neymark & Judkoff, 1995), benchmarks the annual and peak demands for heating and cooling with those originated from a series of other building performance tools. The validation indicates annual and peak heating demands within the range of the benchmark. The results for the annual cooling peak and demand are off target, respectively -20.4% and -14.9%, compared to the benchmark minimums. Since cooling is not considered in this work, this deviation will have no influence on the accuracy of the case study conducted with this DHCM.

The second validation, is conducted by simulating the space heating demand of a large office building and comparing it with measured gas consumption data (Figure 8, left graph). The results of the comparison are evaluated by calculating the CV-RMSE (Coefficient of Variation - Root Mean Square Error) and the MBE (Mean Bias Error) for an hourly and monthly time step and comparing them with the ASHRAE guidelines (ASHRAE, 2002). The CV-RMSE value indicates the overall magnitude of the errors and the amount of scatter normalized to the mean of the observed values, while the MBE indicates the overall deviation between the simulated and measured data. Furthermore, the MBE indicates how much error would be introduced into annual energy consumption estimates, therefore minimizing MBE has priority for this case study in which the annual performance of the DH system is evaluated.

The resulting CV-RMSE and MBE values are unacceptable for both time steps (Table 4). To reduce the errors value the model is calibrated using the calibration signature method (Wei, G., Liu, M., and Claridge, 1998). The calibration is able to decrease the MBE value for both hourly and monthly time steps and the CV-RMSE for its monthly time step to well within the calibration guideline specifications (Table 4). However, the CV-RMSE value, at an hourly time step, indicates 122%. After analysis, this significant share is caused by operational schedules for the HVAC that were changed randomly at daily basis and during weekend operation. The simulated results are filtered excluding weekends and outliers in the CV-RMSE calculation. This resulted in a decreased CV-RMSE, for an hourly time step, from 122% to 55% which is still outside the guideline specification, however in better agreement (Figure 8, right graph).

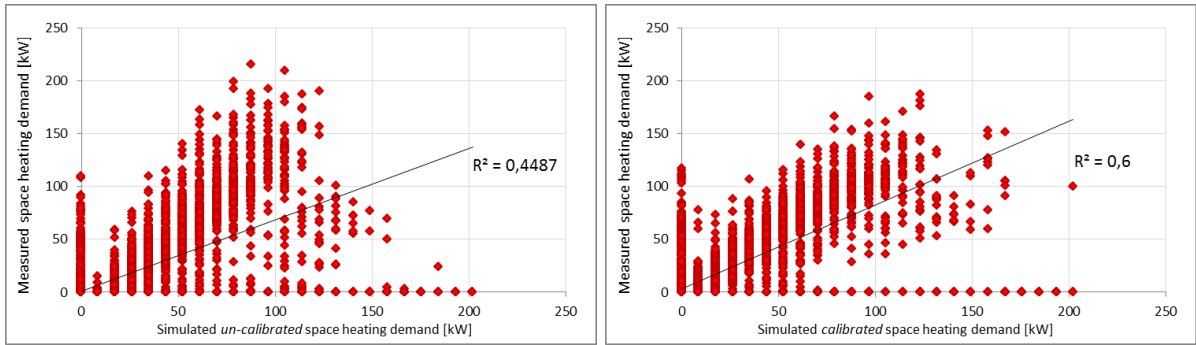


Figure 8: Space heating demand: measured versus simulated un-calibrated (left) and calibrated (right)

To summarize, the hourly CV-RMSE value (Table 4) of the calibration does not satisfy the guideline specifications, the residual CV-RMSE can be attributed to the following uncertainties: Firstly, specification uncertainties in the assumed input parameters that are introduced due to incomplete documentation of building characteristics and noticeable human-introduced changes in HVAC set-points during the year. Secondly, modelling uncertainty related to the ISO model implemented in Dymola and assumptions made (e.g. a one zone model is used and untraceable values in the ISO specifications). Thirdly, numerical uncertainty introduced by Dymola in the discretization of the model. And fourthly, scenario uncertainty introduced by the climate file obtained from a climate observatory located 15 km away from the actual building site.

Table 4: Results of the ISO calibration

Measure	Guideline		Un-calibrated		Calibrated & Filtered	
	Hourly	Monthly	Hourly	Monthly	Hourly	Monthly
MBE	< 10%	< 5%	-26%	-26%	-0.4%	-0.6%
CV-RMSE	< 30%	< 15%	149%	30%	55%	11%

### 3.3.4 Thermal energy storage

The buildings connected to this DH system have a fluctuating space heating demand at a daily and seasonal level. Implementing a TES will flatten the short and high demand peaks (Basciotti & Judex, 2011) occurring during the early morning on the generation side. The flattening of the peaks could increase the utilization of the biomass gasifier which has a limited maximum thermal output and reacts slowly to the changes in demand. Thus, limiting the use of the fossil fueled gas boiler which will decrease operational expenditures and CO<sub>2</sub> emissions.

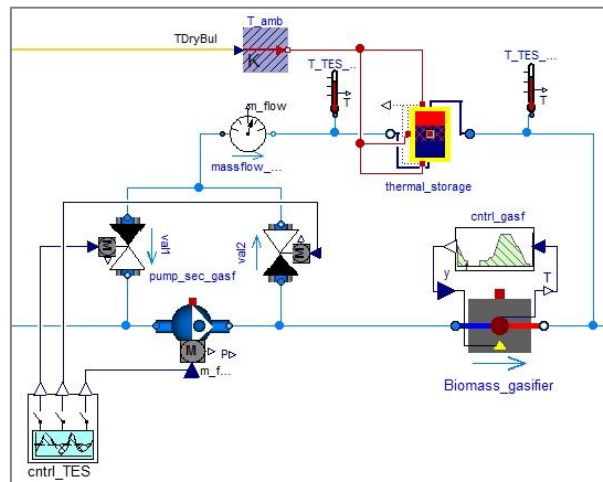


Figure 9: Model view, TES system integrated in power plant

A model of a 100 m<sup>3</sup> stratified hot water storage device is integrated. The stratification, layering of water temperatures inside the storage vessel, occurs by injecting water into a temperature corresponding layer, increasing the energy density that can be stored. Heat loss of the TES is computed by considering the temperatures of the various volumes as a function of the ambient temperature.

The stratified storage system is controlled by two 2-way valves (Figure 9) which enable loading or un-loading (Frederiksen & Werner, 2013). When valve 1 (val1) is opened, cold water is extracted from the bottom and used as supply for the gasifier. Whereas valve 2 (val2) is opened, hot water is extracted from the top and delivered to the distribution system resulting in additional peak power. The control algorithm is designed as a reactive algorithm by continuously monitoring the conditions and adjusting the valves and fluid flow correspondingly. During the nights and weekends, loading can commence if the heating demand is below the maximum thermal output of the biomass gasifier. During the day, unloading can begin if the heating demand exceeds the maximum thermal output of the gasifier. The latter will not only result in valve control, but also in increased fluid flow, so that the fluid originated from the TES can be considered as additional peak flow.

## 4. RESULTS AND DISCUSSION

The simulation results obtained from the DHCM are presented and discussed for two DH designs, with and without TES.

### 4.1 DH case without TES

The energy performance of this DH system is evaluated based on an energy balance, with a focus on the distribution losses, space heating demand by the consumers and the utilization of the biomass gasifier. The energy flows across the system are expressed using the first law of thermodynamics (Incropera & DeWitt, 2007), which states that the total energy of an isolated system is constant, and is reflected on this system (eq.1).

$$Q_{consumers} + Q_{gasifier} + Q_{peak\ boiler} + Q_{emergency\ chiller} + Q_{losses} + Q_{auxiliaries} = 0 \quad (\text{eq.1})$$

The thermal distribution losses (Figure 10) consist of two patterns, namely the annual cosine shaped temperature fluctuation which depends on the ambient temperature. And, the distribution temperature related pattern which fluctuates hourly and depends on the heating demand. During the year the thermal losses for this specific DH system vary from 30 kW<sub>th</sub> to 41 kW<sub>th</sub>, and in total, they account for an annual thermal loss about 1,077 GJ (Table 5). Approximately 6.9% of the total annual space heating demand.

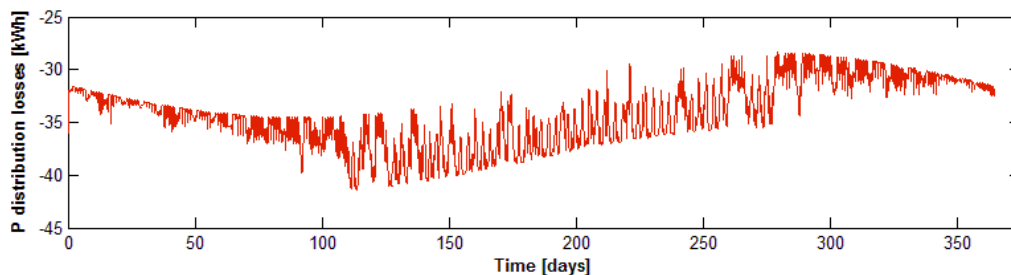


Figure 10: Thermal distribution losses

The space heating demand of the 8 institutional buildings is measured in the model at each building and the total demand is displayed in Figure 11. The analysis of this graph indicates a fluctuating heating demand with peaks exceeding 3 MW<sub>th</sub> during the colder seasons and very low space heating demand required in the warm seasons. The total space heating demand by consumers (Table 5) is about 15,523 GJ per year, matching nicely with the 15,250 GJ per year obtained from the traditional DHCM. However, in this new DHCM the building characteristics could be changed (e.g. better insulation or a heat recovery ventilation system) to evaluate the effect of a changing space heating demand on the system performance.

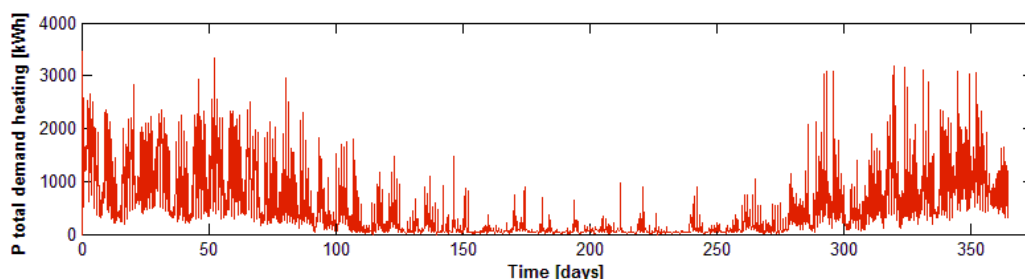


Figure 11: Total demand for space heating by the consumers

The utilization of the biomass gasifier (Figure 12, top graph) is evaluated by computing the effective utilization. This is the heat originated from the biomass gasifier effectively used for system operation, thus excluding heat extracted from the system by the emergency chiller (434 GJ per year) or, if applicable, losses from the TES. This indicates about 4,371 hours of

effective utilization of the biomass gasifier (Table 5). This is 418 hours or 9.6 % higher than computed with the traditional DHCM (about 3,953 hours), and even higher than its results with TES, indicating a utilization of about 4,311 hours. The reason is likely due to the thermal capacity of the DH system itself that acts as a thermal buffer, flattening the demand peaks at the generation side, which has a positive effect on the utilization of the biomass gasifier.

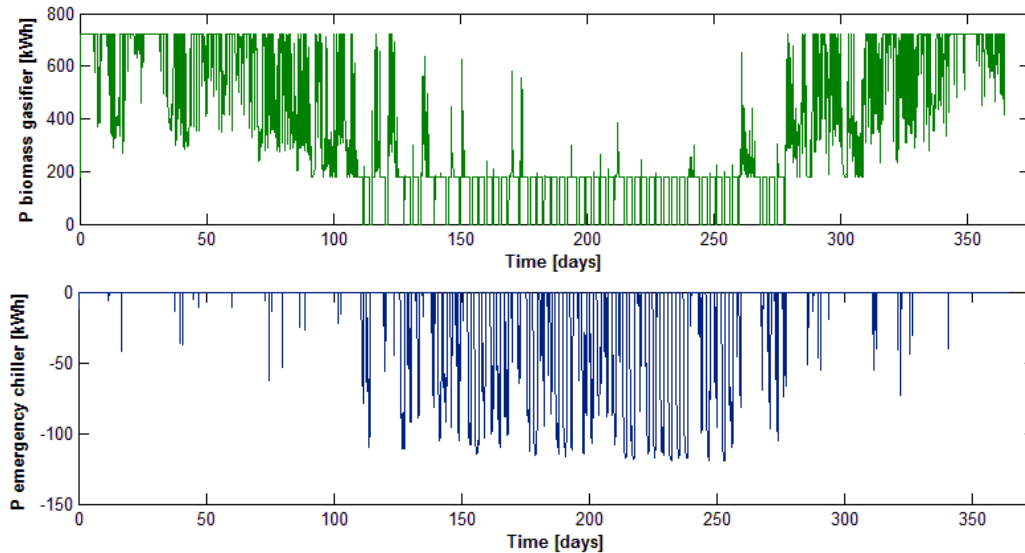


Figure 12: Generated heat by gasifier (top) and extracted heat by emergency chiller (bottom)

The space heating demand exceeding the maximum thermal output of the biomass gasifier is generated with the peak boiler (Figure 13). In this case almost 78.8 % of the maximum peak is delivered by the peak boiler and accounts for 33% of the total energy demand.

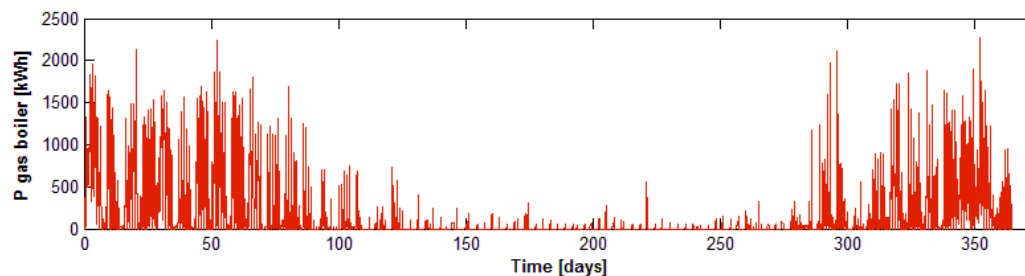


Figure 13: Generated heat by peak boiler

## 4.2 DH case with TES

For the second case the power plant configuration with TES is used. During the analysis of the first results new insights led to additional modifications that resulted in better operation and performance of the system. These modifications were related to controls (e.g. timing settings and statement adjustments) and components (e.g. increased buffer size from  $100 \text{ m}^3$  to  $150 \text{ m}^3$ ). Figure 14 (top graph) shows that the thermal output of the biomass gasifier is at its maximum ( $720 \text{ kW}_{\text{th}}$ ) between the peaks of the total heat delivered by both the heat generation loops. This is due to the TES being loaded at that time (bottom graph). When the total heat delivered peaks the heat delivered by the gasifier loop (middle graph) rises up to about  $2000 \text{ kW}_{\text{th}}$ . This is due to the unloading of the TES at that moment (bottom graph), which delivers additional peak power to the gasifier loop. Furthermore it can be seen that during the weekends (starting at 35<sup>th</sup> and 42<sup>th</sup> day) the TES is able to be loaded to nearly 98% of its capacity, which is set to be the maximum. During the first day after the weekend (37<sup>th</sup> and 44<sup>th</sup> day) the fully loaded TES enables delivery of heat for a longer period compared to

other weekdays. During the nights of the weekdays there is not enough overcapacity of the biomass gasifier to effectively fill the TES and therefore it is not always loaded up to 98% of its capacity. This all indicates that the TES is effectively controlled and that the storage capacity is efficiently being used.

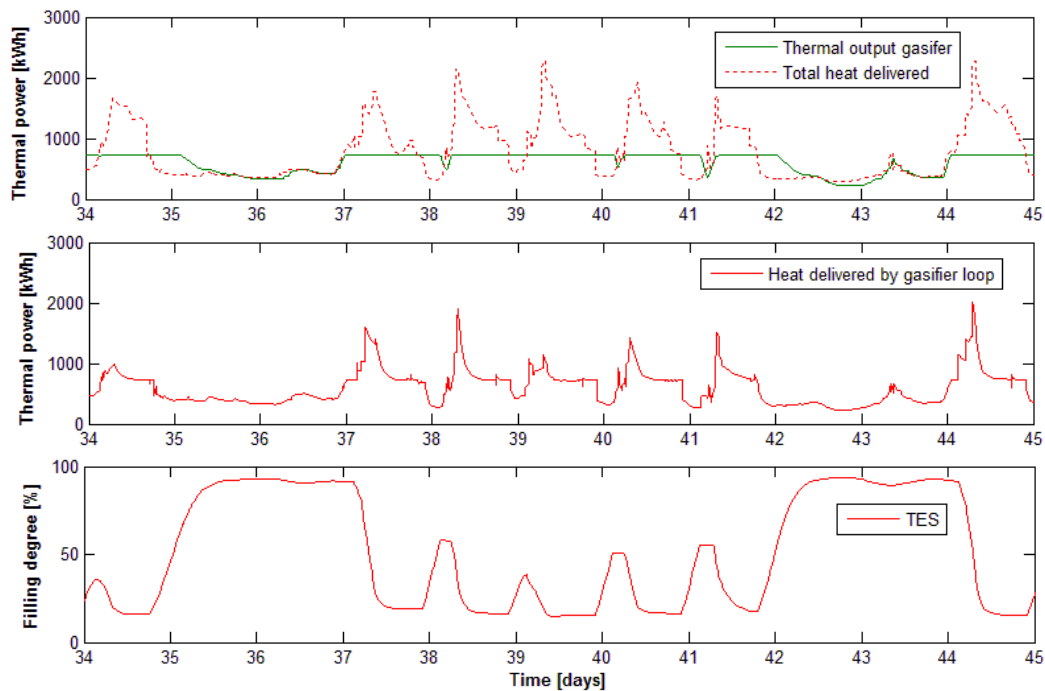


Figure 14: Total heat delivered by loops (Top), Heat delivered by gasifier loop (middle), Filling degree TES (bottom)

The full annual simulation with the TES system shows an increase of the utilization of the gasifier to 4,664 hours, 293 hours or 6.7%, compared to the DH case without TES (Table 5). In absolute as well as relative terms this is less than adding TES in the traditional DHCM. Even while the new DHCM is considering a 150 m<sup>3</sup> TES system and the traditional DHCM is considering a 100 m<sup>3</sup> TES system. The lower gained utilization could be due to the earlier gained utilization in the case without TES, which limits the potential improvement of the gasifier utilization by integrating a TES.

Table 5: Overview of system performance indicators

Computational Model (CM) + Scenario	Energy demand			Gasifier	
	Consumers [GJ/a]	Losses Distr. [GJ/a]	Losses TES + Chiller [GJ/a]	Ratio over peak boiler [/]	Eff. utilization [hr.]
Traditional CM	15250	1300	190	0.61	3953
Traditional CM + TES	15250	1300	310	0.66	4311
New CM	15523	1077	434	0.67	4371
New CM + TES	15523	1077	545	0.71	4664

Nonetheless, computing the DH case with TES, using the new DHCM, shows an overall increase of 353 hours or 8.2% in utilization of the biomass gasifier compared to the traditional DHCM. This is a substantial increase of the utilization that, during a feasibility study, would contribute to the economic and the environment impact of this case study.

## 5. CONCLUSION

This paper describes the development process of a DHCM, considering heat generation, heat distribution, heat demand and TES. The use of the object-oriented modeling language Modelica has proven to be suitable and beneficial for increasing the modeling capabilities during early-design phase feasibility analysis of projects.

The evaluation of a DH case study with TES using the new DHCM shows an 8.2% (353 hours) higher utilization of the biomass gasifier than when compared to a traditional DHCM. Differences in utilization of components of this magnitude can substantially influence the economic feasibility and environmental impact of a project. Since, the biomass gasifier can deliver an additional 353 hours of renewable combined heat and power.

The realistic behavior and natural representation of the systems modeled in Modelica contribute to the understanding of the thermodynamic and control related systems. This can be an advantage for educational purposes for students or academics and even for engineering professionals. Furthermore, for commercial purposes, where deadlines constrain the effort, the quick development capability that Modelica offers as a simulation language, could be a great advantage.

Efficient use of Modelica based models and systems will require additional development and possible customization per company (e.g. own control strategies, system designs). The development of blocks, models and control strategies will require collaboration in multi-disciplinary fields and inter-organizational levels. The development of more elaborate application-oriented guidelines (e.g. designing controls) could further improve the new-users experience.

The DHCM described in this paper is likely to contribute to future early-design phase projects for Cofely, delivering and evaluating system configurations for renewable DH systems. The improved accuracy and level of detail, compared to the traditional DHCM, could make a difference for considering the feasibility of a particular DH project. Thus, this new DHCM can result in additional renewable energy projects being delivered, that otherwise would be labeled as unfeasible, and indirectly contribute to the global challenges concerning climate change mitigation.

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