SHINE DOCTORAL SCHOOL – RESULTS FROM SIX PHD STUDIES ON LARGE SCALE SOLAR THERMAL

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Abstract – The Solar Heat Integration NEtwork (SHINE) is a European research school in which 13 PhD students in solar thermal technologies are funded by the EU Marie-Curie program. It has five PhD course modules as well as workshops and seminars dedicated to PhD students both within the project as well as outside of it. The SHINE research activities focus on large solar heating systems and new applications: on district heating, industrial processes and new storage systems. The scope of this paper is on systems for district heating for which there are six PhD students, five at universities and one at a company. The initial work concentrated on literature studies and on setting up initial models and measurement setups to be used for validation purposes. The measurements have been used for validating simulation models, including those used for extending the capabilities of the planning tool Polysun to simulate smaller district heating systems. Some results of these studies are presented in the paper. The PhD students will complete their studies in 2017-18.

1. INTRODUCTION

Since 2006 there has been a European collaboration on graduate education within the field of solar thermal, SolNET (Jordan et al., 2007). The initial four years was funded mainly by the EU Marie-Curie program but also by national funding in the different participating countries. Seven courses for PhD students were taught and 10 PhD students were trained in this initial project. The network was so successful that the collaboration continued after the end of the first project with one PhD course planned per year. The first PhD projects funded within SolNET focused mostly on small scale systems. A new project funded by the EU Marie-Curie program, Solar Heat Integration NEtwork (SHINE), started at the end of 2013 and is focused on large scale systems and thermal storage (Jordan et al. 2014). In total 13 PhD students are funded in this project, of which six have projects that are related to solar district heat. Five Ph.D. courses have been organized by the participating universities, one of which covered large scale collector fields for district heating or process heat.

The work is split into three different work packages: WP1, focusing on solar district heating (and the subject of this paper); WP2, studying solar heat for industrial processes; and WP3, focusing on sorption processes and materials. The aim of this paper is to present the six projects related to solar district heating and the first results from them.

2. PHD PROJECTS

The six PhD studies, described in the next sections, range from detailed modelling of hydraulic networks to development of new tools for simulation of systems. However, there is a significant synergy between the projects, with several joint publications in progress.

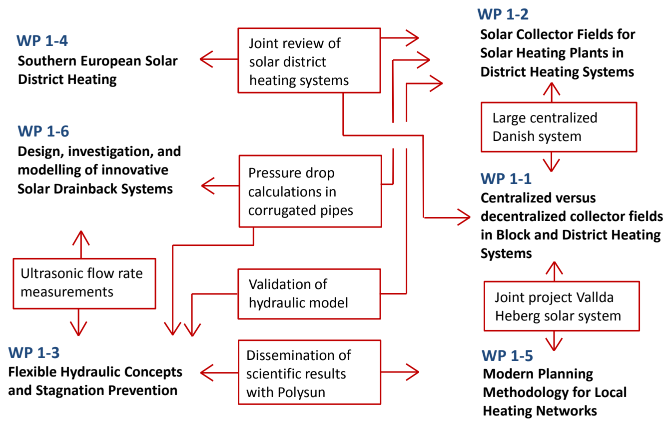


Figure 1*. The PhD studies and interactions between them.*

2.1 Techno-economic analysis of SDH systems (Högskolan Dalarna)

The PhD project at Högskolan Dalarna (SERC) was initiated spring 2014 by Christian Nielsen, who left the project in spring 2015. The work was continued by Martin Andersen starting autumn 2015 and is now ongoing under the supervision of Chris Bales (Dalarna University) and Jan-Olof Dalenbäck (Chalmers University of Technology). The main objective of the project is to derive the techno-economic boundary conditions for profitable integration of solar heat into district heating networks. These boundary conditions shall be provided for both district heating systems built anew and for systems supported with solar heating by means of retro-fit.

The method applied consists of two parts. To firstly examine the operational characteristics of existing solar district heating systems. Then, based on the operational experience from these systems, to collaborate with contractors/utility companies to identify the potential improvement(s) in system configuration and operation. Secondly, suggested improvements are investigated by employment of a validated TRNSYS model of the respective system.

The first system investigated is a novel block-heating system of the Vallda Heberg residential area outside of Gothenburg, Västra Götaland County (Figure 2). The system consists of buildings at near passive house standard with solar thermal integrated at both heating plant and substations. The work is conducted in collaboration with engineering consulting firm Andersson & Hultmark and municipal housing company Eksta Bostads AB, who were responsible for the project.

Preliminary results for two of the four substations in the heating network show that the system is working as intended and that the 40% solar fraction of heat demand is likely to be met (Nielsen et al. 2014). A validated TRNSYS model of one of these substations has been made and simulations will be compared with those from a Polysun model in a future publication.

Current work is focused towards the development of a fully functioning, albeit simplified TRNSYS model of the entire heating system, calibrated against measured data. The intention is to investigate different heat distribution concepts and solar system integration points to show if, and how, it is possible to improve performance and reduce investment cost of the studied system.

Future work will focus on retro-fit of existing district heating networks with solar thermal, in addition to the methodology used to evaluate the profitability in integration of solar thermal into district heating networks.

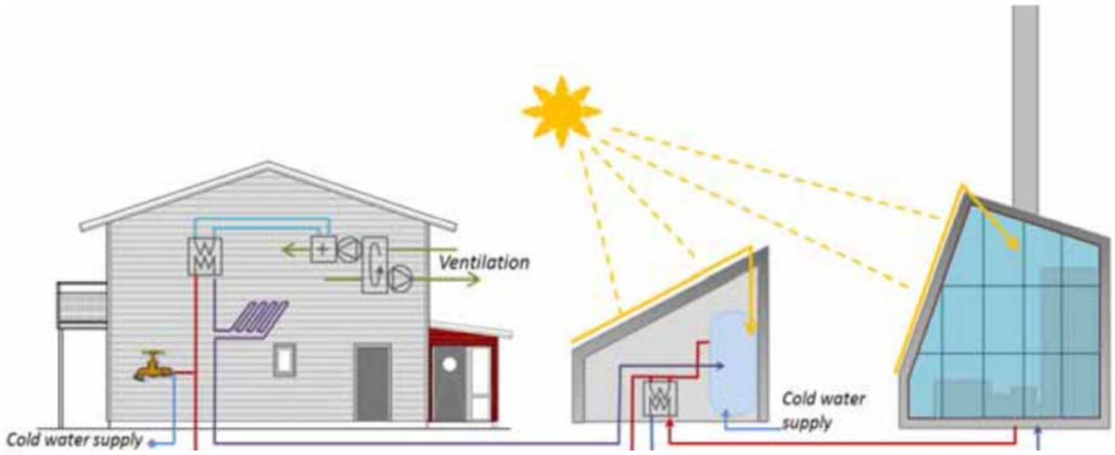


Figure 2: *A simplified schematic of the novel heat supply system at Vallda Heberg.*

2.2 Solar Collector Fields for District Heating (Technical University of Denmark, DTU)

The PhD project at DTU focuses on the development of detailed simulation models of large scale solar collector fields for DH applications. Given the area of research, a strong collaboration and exchange of information have been established with the Danish company Arcon Sunmark A/S, the world's leading manufacturer of large-scale solar thermal plants for DH. The project is carried out by the PhD Candidate Federico Bava, under the supervision of Assoc. Prof. Simon Furbo (DTU), Assoc. Prof. Jianhua Fan (DTU) and CEO Søren Elisiussen (Arcon-Sunmark A/S).

During the project detailed simulation models for different solar collector types and differently designed and controlled solar collector fields are developed and validated against measurements from the solar collector test facility at DTU and from Danish solar heating plants. The main model of the collector field is developed in TRNSYS, but it also makes use of a Matlab code to evaluate the flow distribution in the collector field. Presently, the flow distribution in Danish solar collector fields is regulated by balancing valves in each collector row, set in such a way that a uniform temperature is reached at the end of each row in nominal operating conditions. However, it is not exactly known how the flow distribution is when the field is operated in different conditions. Hence a Matlab code dealing with this aspect has been developed. Figure 3 shows an example output of the developed model. More specifically, the diagram shows the flow distribution at different flow rates in the collector field at Høje Taastrup (Denmark), when operated at supply/return temperature of 55/95 °C.

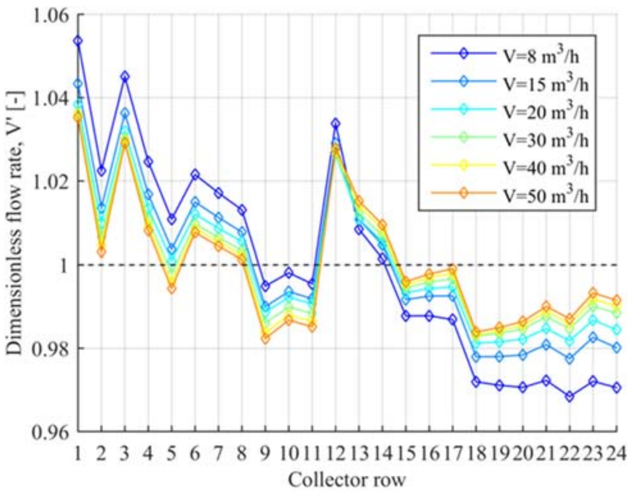


***Figure 3**. Example of modeled flow distribution in Høje Taastrup solar collector field.*

In order to evaluate the flow distribution in the collector field, the relation between flow rate and pressure drop in all the components of the system needs to be known. The solar collectors are surely the key component of these systems. So, a numerical model to evaluate the pressure drop and flow distribution in a U-type harp collector has been developed (Bava & Furbo 2016). As an example, the pressure drop dependence on the flow rate and fluid temperature of a 35% propylene glycol/water mixture is shown in Figure 4.

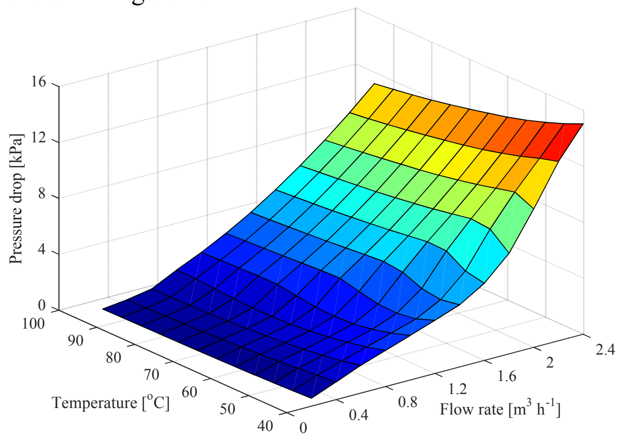


***Figure 4**. Modeled pressure drop of Arcon Sunmark HTHEATstore 35/08 collector as function of temperature and flow rate for 35% propylene glycol/water mixture.*

Additionally, given the effect of the flow regime on the collector thermal efficiency (Bava & Furbo 2014; Bava et al. 2014), a new TRNSYS type was developed starting from the existing Tess type 539. This new type is able to correct its efficiency parameters depending on the flow regime conditions in the absorber pipes.

Arcon-Sunmark produces collectors either with or without polymer foil used as convection barrier. So, another aspect which was investigated was the performance-wise and economic optimization of a single collector row, making use of both of these collectors (Bava et al. 2015).

2.3 Flexible hydraulic concept and stagnation prevention (University of Innsbruck)

Considering the diversity of solar products in the market, design concepts and hydraulic schemes in large solar systems are various and steadily evolving in an effort to enhance thermal performance. Barriers to further development of large solar thermal systems is addressed in the present PhD work with the focus on hydraulics as an integral part of large solar thermal systems. This study is made by Alireza Shantia and supervised by Prof. Wolfgang Streicher at the Unit for Energy Efficient Buildings of the University of Innsbruck. The main objective of the research is to develop a flexible tool for evaluating complex thermo-hydraulic networks including: single flat-plate collectors, solar collector fields and district heating networks with an emphasis on pressure drop and flow distribution following the previous experience of the researcher on thermal performance of solar collectors (Shantia, 2014). The possibilities of both stand-alone and co-simulation are taken into consideration in the development of the tool. From a system perspective, the project relies on the mature knowledge in the field of water distribution systems, in which several numerical algorithms have been introduced over the last eight decades to handle the non-linear nature of pressure drop in hydraulic analysis of elaborated isothermal systems. The Global Gradient Algorithm (GGA) was implemented in the tool that takes advantage of so-called Lagranigan Newton-Like methods to minimize pressure-loss equations subject to mass conservation as equality constrains in junction nodes (Todini, et al., 1988). It makes it possible to calculate meshed grids with distributed pumps in the system. The GGA was adapted in this work to non-isothermal conditions in thermal systems where the effect of temperature on density and viscosity is considerable and should be taken into account for accurate hydraulic calculations. From a component perspective, the work has focused on deriving pressure drop model for key elements in solar systems (e.g., collectors, pumps, junctions, valves and etc.) in the laminar and turbulent regimes and also on finding pragmatic solutions to handle uncertainties in the estimation of pressure drop in the transient region, which is likely to happen partially or entirely in collector fields at low flow rates.

The tool is currently being optimized and calibrated against experimental data for system and component perspectives. Further development might be required depending upon boundaries in case studies. The major part of the calibration steps is carried out by courtesy of S.O.L.I.D – a leading Austrian company in the field of large-scale solar thermal energy plants – through collaboration on the MeQuSo plant in Graz (Figure 5). This plant comprises four collector fields with a total capacity of 5 MW_{th} all connected to a central pump station, where it feeds the district heating network of Graz. Special attention is paid to the largest collector field (CF-1) with a total aperture area of 2,277 m^2 in which, due to involvement in other ongoing research projects, different types of collectors from a number of manufactures are installed and examined. High resolution measurement data for temperature and flow rate in CF-1 provides a unique opportunity for the evaluation of the tool.

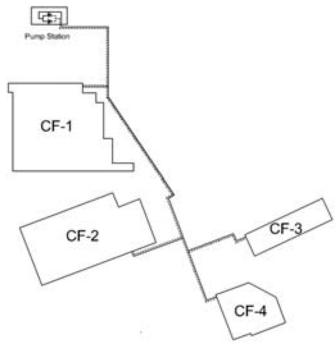


***Figure 5**. Collector fields in the MeQuSo plant in Graz.*

Precise estimation of the pressure-loss in collectors as key elements in solar systems, is a prerequisite for correct prediction of the hydraulic behaviour of the entire collector field. Therefore, validation of the pressure-loss model of all types of collectors is the first step of the calibration procedure of the presented tool.

ARCON HT-SA 35/10, a harp U-shaped collector with a gross area of 13.57 m^2, is the most commonly used type in the MeQuSo fields, allocating 46.6% of the total aperture area installed in CF-1. The collector is 2,275 mm wide and 5,965 mm long with 18 absorber tubes each 5,800 mm long, 9.1 mm in diameter evenly spread with intervals of 122 mm. Figure 6 shows a comparison between simulation and experimental data points, measured at the Technical University of Denmark, where the flowrate and the inlet-outlet mean temperature vary in the ranges of 0.51-2.6 m^3/h and 70.5-77.5 °C respectively. It can be seen that the model can successfully estimate the overall pressure drop of ARCON HT-SA 35/10. A similar procedure is followed for other type of collectors in CF-1 and then the model will be extended to the entire field. The last step of validation is to model all four collector fields as a network as well as the central pump station comprised of two parallel centrifugal pumps, in which the operation points of the system for single and dual pumping are calculated by the tool.

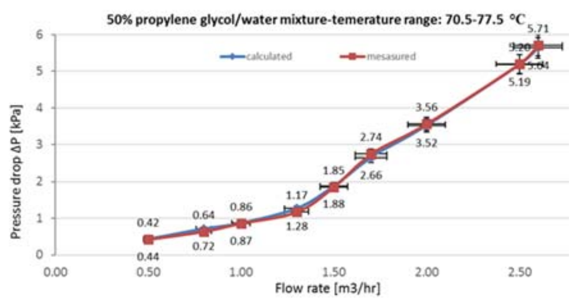


***Figure 6.** The overall pressure drop of ARCON HT-SA 35/10*

2.4 Flexible hydraulic concept and stagnation prevention (Sampol)

The PhD focuses on the operation and optimization of a hybrid power plant which covers the demand of a District Heating and Cooling Network (DHC) and the maximization of solar generation. To do so, it is required to develop electricity price and thermal demand forecasting tools, which works together with an energy simulator. The simulator determinates generation strategies by optimizing the production mix that minimizes the energy cost and maximizes renewable energy fraction. This leads to an optimization of the power plant operation and integration of the solar field. The project is carried out by the PhD candidate Nicolás Pérez de la Mora under the supervision of Vincent Canals and Victor Martinez Moll at University of Balearic Islands (UIB) and it is placed at the company Sampol Ingenieria y Obras S.A in Mallorca, Spain.

Parc Bit is the hybrid power plant under study and it is located in Palma of Majorca, Spain. This power plant comprises two Combined Heat and Power (CHP) diesel engines, a biomass burner, a diesel burner, solar collector field, two absorption chillers and electric chillers as backup (Figure 7). Therefore, the power plant is able to generate heating, cooling and electricity and thus the power plant obtains revenue from injecting electricity into the grid and supplying thermal energy to the DHC. To maximize the plant's revenue it is necessary to develop algorithms able to provide energy generation strategies to fit generation and demand curves.

In order to guide the power plant manager with optimal generation strategies a power plant simulator is developed. The tool has been develop jointly with Politecnico di Torino (PoliTo) and it is able to optimize a multi-energy node power plant in different time horizons (Perez-Mora et al., 2016a). This simulator requires information such as thermal and electric demand to fulfill, climatic conditions, power plant configuration and machine behavior in different generation points. As a result the tool provides the schedule of the generation machines, primary energy consumption and total revenue for the time horizon considered.

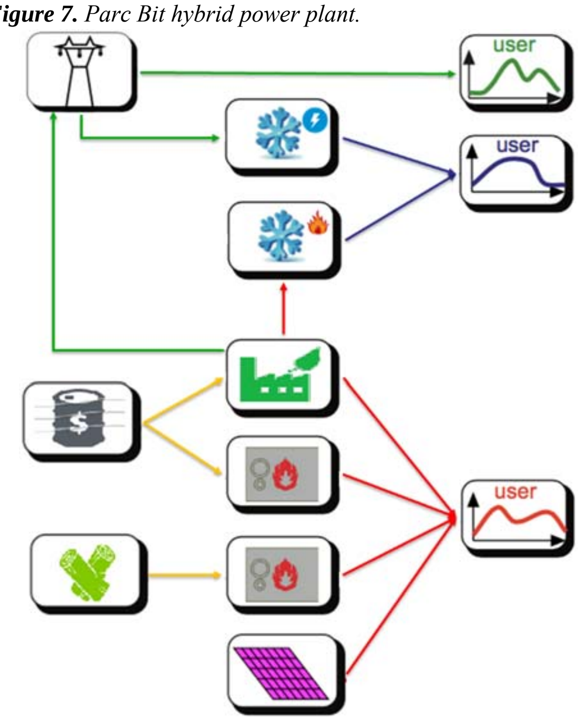
A two cores forecasting tool was developed based on ARIMAX (Auto Regressive Integrated Moving Average with Explanatory variables) and ANN (Artificial Neural Networks) methods in order to obtain the future electricity prices of the Spanish wholesale energy market and DHC thermal demand. Those values are fed in to the optimization tool to determine future generation strategies.

Heat losses in the DHC distribution are considered as part of thermal load to be fulfilled by the power plant. A calculation tool has been developed in order to have an accurate estimation of the thermal losses in a 4 pipes DHC system. In such system it is very important to consider the influence between heating and cooling pipes and their working temperatures. The tool also optimizes the pumping cost taking into consideration the cost in generation for the thermal lost and the electricity cost of the pumps circulating the water in the network (Perez-Mora et al., 2016b).

A solar generation forecaster has been developed, again using two forecasting cores (ARIMAX & ANN) to estimate the future solar thermal generation that can be expected at Parc Bit (Perez-Mora et al., 2015). By using the solar thermal forecaster this generation can be fed to the optimizer, included in the future generation schedule and therefore maximizing the solar fraction by avoiding overlaps with the CHP thermal generation schedule.

The next stage will be to evaluate the results of the different optimization scenarios and the real-life power plant operation. This comparison will show the influences of forecasting error in the power plant revenue and the differences between the real-life operation and the optimal one. The aim of these comparisons is to pursue modif real-life generation strategies to improve the power plant management and the maximization of solar fraction.

Figure 7. *Parc Bit hybrid power plant.*



2.5 Modern planning methodology for local heating networks (Vela Solaris AG)

The PhD project at the software company Vela Solaris AG is pursued by Artem Sotnikov and supervised by Andreas Witzig at Vela Solaris and Wolfgang Streicher at the University of Innsbruck. The goal was to cover larger and more complex thermal systems. In close collaboration with the software engineers of Vela Solaris the models of the heat demand from district heating systems are to be implemented. Several heat sources such as solar collectors, geothermal probes, power and heat cogeneration as well as the various ways for heat storage were already available at project start. Therefore, the work was focused on extension of existing models to make them more suitable for district heating cases. The main aims are to develop and validate a powerful and user-friendly tool which supports the planning of solar district heating networks based on the well-known tool Polysun.

The methodology of the study has been defined. Several existing/new models were extended/developed in Java programming language, which allows applications to have fast computing time as well as being flexible for possible changes and extensions. Developed models are being calibrated against TRNSYS simulation software.

The first task was the extension of Polysun`s building model to cover multiple residential units within one system boundary (see Figure 8) (Sotnikov, Witzig and Streicher, 2015). This goal also required the extension to models of heating elements and system components which are subject of heat interaction with building (e.g. storage tank).

The next task was to extend several existing models to make them more suitable for district heating application. In the scope of this task a model of a storage tank allowing the user to define the number of nodes was developed, as was a model for buried pipe. This makes it possible to simulate heating plants (with large storage tanks) and distribution networks. In order to check developed models, a real system at Vallda Heberg has been modelled in Polysun and calibrated against measured data. An article on this and comparison with TRNSYS results is being prepared together with Christian Nielsen a former PhD student at Högskolan Dalarna and Martin Andersen PhD student at Högskolan Dalarna.

The next stage has started, which is development of a multi-zone building model. A number of physical models of building components were implemented and proven by means of JUnit tests. Now an interface between Polysun and the new model shall be built. Then it will be calibrated against TRNSYS`s Type 56 building model.

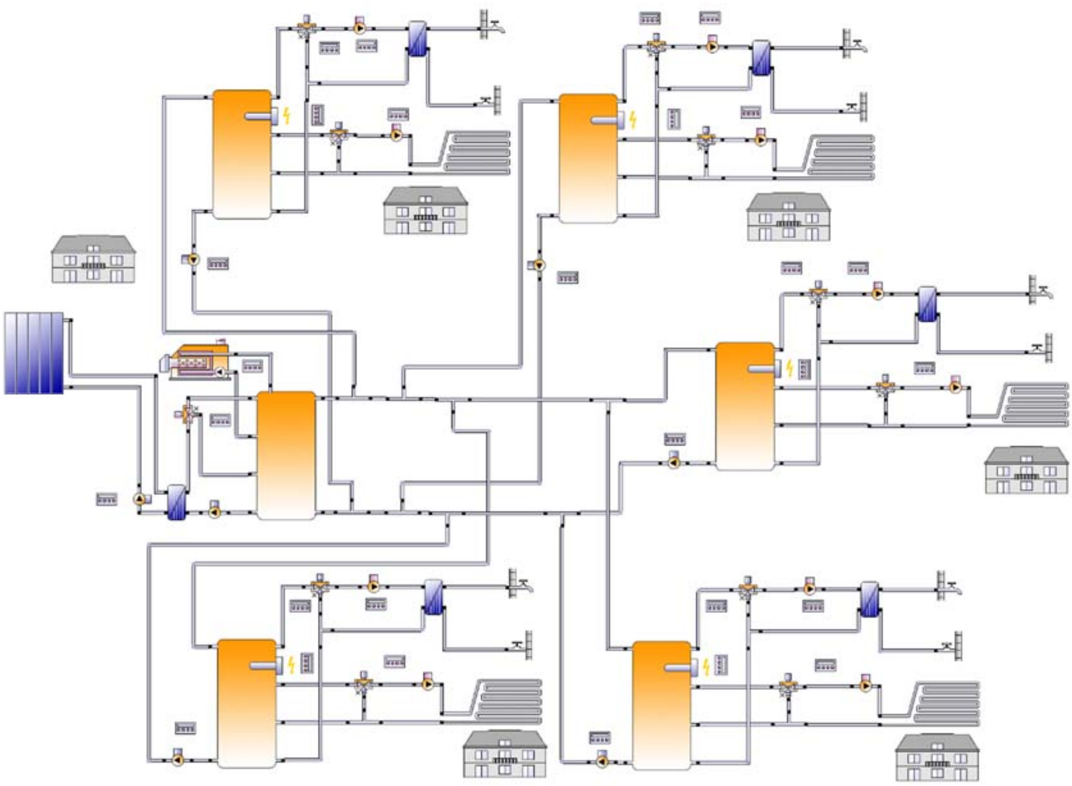


***Figure 8**: Two-line decentralized solar district heating system with central unit.*

2.6 Investigation of the cost-performance improvement potential of the drainback technology (University of Kassel)

The project is carried out by Y. Louvet and supervised by Klaus Vajen from the University of Kassel. Drainback refers to a particular type of solar thermal systems for which frost and overheating protections are provided by the emptying of the collectors when the circulation pump is not in operation. Due to this feature, performance improvements and costs reduction might be achieved.

In a first step, an intensive literature research was carried out to gather, analyse and summarize available knowledge related to drainback systems (DBS). Despite being an old technique, few scientific publications were found on the topic. The major source of information turned out to be patents. The results were published in a joint journal article with the Technical University of Denmark (Botpaev et al., 2016). A mapping of possible system designs as well as state-of-the-art components resulted from this work. Moreover, specific technical issues related to the design and operation of DBS were identified.

Practical knowledge on DBS was gathered from the monitoring of several large systems (with a collector area greater than 100 m²) installed by the company EnerSolve GmbH, located in Kassel, Germany. In particular, a DBS without collector side heat exchanger dedicated to drying of hay bales, consisting of a collector area of 127 m² and a total storage volume of 42 m³, was studied in detail and the findings were presented in Jordan et al. (2015) and Louvet el al. (2015). The analysis made it possible to optimize the operation of the plant, notably with regards to the control strategy.

Based on the actual configuration of the plant, a detailed model was also built up for simulation purposes in TRNSYS 16. Several configurations were then derived, simulated over the drying season from May to September and compared as detailed in Figure 9. The objective was to compare the thermal performance ($f_{sav,therm}$) as well as the pumping energy needs ($f_{sav,\ ext}$) of the different configurations. A conventional pressurized system was taken as reference. Different drainback designs were also simulated, with and without heat exchanger (HX) in the solar collector loop, and with an antifreeze mixture and pure water as heat transfer fluid (HTF). Moreover, DBS can be operated either with a partially or a fully filled flow pipe. In the latter case, the complete filling of the pipe establishes a siphon. It has a positive impact on the pumping energy needs as it cancels the elevation head but experimental results also showed that it might reduce the thermal performance due to cavitation in the collectors. Two configurations without collector-side heat exchanger, with and without siphon in the flow pipe were also compared. The results of the simulations showed that the performance improvement due to the use of water instead of an antifreeze mixture is relatively small (< 1 %). On the contrary, the systems without heat exchanger on the collector-side perform more than 7 % better than the reference system.

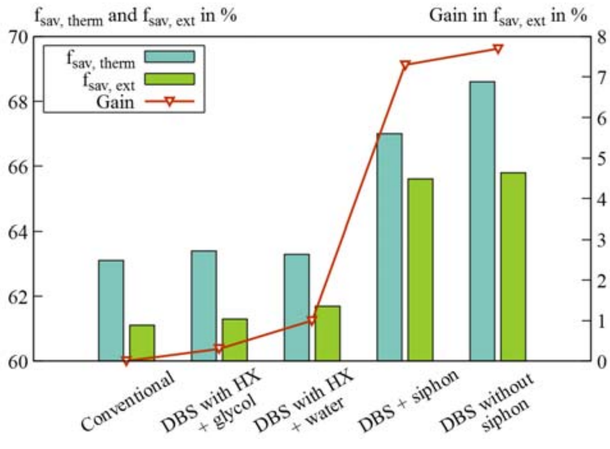


***Figure 9**. Simulated thermal performance during the drying season of a 127 m² solar thermal system for drying hay bales using different system configurations.*

The next steps of the study will consist in simulating a wider range of systems and varying the system parameters. A detailed analysis of the cost structure of solar thermal systems and in particular DBS will also be carried out in order to evaluate the overall cost-performance improvement brought by solar DBS in comparison to conventional systems.

In parallel to these investigations, a method guaranteeing the safe draining of solar drainback systems was developed. It consists in ensuring that no water pocket remains in the solar collector loop after draining. This issue is highly relevant for DBS using water as HTF. The results will be published in a journal paper.

3. CONCLUSIONS

The PhD students in the SHINE project has been active for two and a half years and have made a number of interesting studies for solar district heating. These have been briefly described in this paper, with reference to the more detailed publications that have been produced within the project. In the coming year will be the most productive in publications, with several joint publications.

ACKNOWLEDGEMENTS

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