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PROGRESS AND RESULTS FROM THE 4DH RESEARCH CENTRE

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ABSTRACT

With lower and more flexible distribution temperatures, fourth generation district heating systems can utilize renewable energy sources, while meeting the requirements of low-energy buildings and energy conservation measures in the existing building stock. 4DH is an international strategic research centre located at Aalborg University, which develops 4th generation district heating technologies and systems (4GDH). This technology is fundamental to the implementation of the Danish objective of being fossil fuel-free by 2050 and the European 2020 goals. The research centre is working between 2012 and 2017, with The Danish Council for Strategic Research as main financier and the participating 31 Danish and international companies and universities as co-financiers. Thirteen PhD student projects constitute a vital part of the research centre. In 4GDH systems, synergies are created between three areas of district heating and cooling, which also sum up the work of the 4DH Centre: Grids and components; Production and system integration, and Planning and implementation. This paper presents an overview of the progress and results achieved after more than two years of work. This includes the basic definition paper, the two Heat Roadmap Europe pre-studies, annual conferences, additional demonstration projects, initiated European project proposals, an international PhD course based on the new international textbook, PhD student seminars, all PhD student subjects, and a list of major papers and articles written so far within the research centre.

INTRODUCTION/PURPOSE

With lower and more flexible distribution temperatures, 4th generation district heating systems can utilize renewable energy sources, while meeting the requirements of new low-energy buildings and energy conservation measures in the existing building stock. Another important change in the energy system is the transition from fossil to renewable input into the electricity market. Hereby, traditional CHP plants using fossil fuels will lose its competitiveness in favour of wind and solar power. Therefore, many European district heating systems will lose their traditional heat source. These challenges for district heating systems have earlier been described in [1] and [2].

Labelling this next generation of district heating technology as the fourth generation requires the

definition of the three preceding technology generations.

The first generation of district heating systems used steam as a heat carrier. These systems were first introduced in the USA in the 1880s. Almost all district heating systems established before 1930 used this technology, both in the USA and in Europe. Typical components were steam pipes in ducts, steam traps and compensators. Today, steam distribution can be considered as an outdated technology in district heating systems, since high steam temperatures generate high heat losses, and severe accidents from steam explosions have even killed pedestrians in streets. The condensate return pipes have often corroded, resulting in less condensate returns and lower energy efficiency. Steam is still used as the main heat carrier in the old New York (Manhattan) and Paris systems and is partly used in Copenhagen, while replacement programs have been successful in Hamburg, Salzburg, and Munich.

The second generation of district heating systems used pressurised hot water as a heat carrier, with temperatures mostly over 100°C. These systems emerged in the 1930s and dominated all new systems until the 1970s. Typical components were water pipes in concrete ducts, large shell-and-tube heat exchangers, and material-intensive, large, and heavy valves. The large Soviet-based district heating systems used this technology but with a low level of quality without any local heat demand or flow control in the overall control systems. Outside the former USSR, the quality level was much higher and remnants of this technology can still be found making up older parts of the current water-based district heating systems.

The third generation of district heating technology was introduced in the 1970s and took a major share of all extensions in the 1980s. Pressurised water is still the heat carrier, but the supply temperatures are often below 100°C. This third generation is sometimes referred as Scandinavian district heating technology, since some well-known district heating component manufacturers are Scandinavian companies. Typical components are pre-fabricated and pre-insulated pipes buried directly into the ground, compact substations using braze heat exchangers, and material-lean components. This technology is used for all replacements in Central and Eastern Europe and the former USSR. Almost all extensions and all new systems in China, Korea, Europe, the USA and Canada now use this third generation technology.

The purpose with this paper is to summarise the activities from the start of the Danish 4DH research centre, designed for taking a wide approach for facilitating the development of the new enhanced fourth generation of district heating technology.

METHODS/METHODOLOGY

4DH is an international research centre located at Aalborg University, which develops 4th generation district heating technologies and systems (4GDH). This technology is fundamental to the implementation of the Danish objective of being fossil fuel-free by 2050 and the European 2020 goals. The research centre is working between 2012 and 2017, with The Danish Council for Strategic Research as main financier and the participating 31 Danish and international companies and universities as co-financiers. The total project budget is almost ten million euro during the six years of activity. Currently, the 4DH research centre is the largest academic district heating project in Europe.

The 4DH research centre is headed by professor Henrik Lund at Aalborg University in Aalborg, while professor Brian Vad Mathiesen at Aalborg University in Copenhagen is deputy head with a special coordination responsibility for the PhD students and their projects.

Partners

The project partners are listed in Table 1. These partners are universities, district heating companies, consulting companies, and manufacturers of district heating components. Some international partners come from China, Croatia, and Sweden.

Organisation

In 4GDH systems, synergies are created between three areas of district heating, which also sum up the work of the 4DH Centre: Grids and components; Production and system integration, and Planning and implementation. These areas are organised in work packages.

Work package 1, District Heating Grids and Components: This first area focuses on the research, development and evaluation of low-temperature district heating systems based on renewable energy. The research basically provides new knowledge of the hardware and software technologies of the new generation of district heating systems supplying heat to existing energy renovated buildings and new low-energy buildings.

The hypothesis is that low-temperature district heating, with a general supply and return temperature of about 50°C and 20°C, respectively, can be used in existing district heating systems, if minor modifications are implemented in the systems for room heating and domestic hot water supply of the existing buildings. The immediate implementation of the low-temperature technology (10 years) in existing and new district heating systems and buildings makes it possible to use low-temperature renewable heat from geothermal plants and central solar heating plants as well as waste heat from industrial processes directly and thereby replace fossil fuels and imported biomass in the district heating systems.

Table 1. List of the current 31 project partners.

| | | |
|----|---|---------|
| 1 | Aalborg Forsyning, Varme | Denmark |
| 2 | Aalborg University, Department of Development and Planning, AAU-PLAN & AAU-CPH | Denmark |
| 3 | Aalborg University, Department of Energy Technology, AAU-IET | Denmark |
| 4 | AffaldVarme Aarhus | Denmark |
| 5 | Chalmers University of | Sweden |
| 6 | COWI | Denmark |
| 7 | CTR | Denmark |
| 8 | Danfoss | Denmark |
| 9 | DESMI | Denmark |
| 10 | EMD | Denmark |
| 11 | Fjernvarme Fyn | Denmark |
| 12 | Grøn Energi | Denmark |
| 13 | Halmstad University | Sweden |
| 14 | Kamstrup | Denmark |
| 15 | HOFOR | Denmark |
| 16 | Linnaeus University | Sweden |
| 17 | LOGSTOR | Denmark |
| 18 | NIRAS | Denmark |
| 19 | Planenergi | Denmark |
| 20 | Rambøll | Denmark |
| 21 | Ringkøbing-Skjern Kommune | Denmark |
| 22 | SPX | Denmark |
| 23 | Technical University of Denmark – Department of Civil Engineering, DTU-BYG | Denmark |
| 24 | Technical University of Denmark – National Laboratory of Sustainable Energy, DTU-RISØ | Denmark |
| 25 | Tsinghua University | China |
| 26 | University of Southern Denmark, SDU | Denmark |
| 27 | University of Zagreb | Croatia |
| 28 | VEKS | Denmark |
| 29 | Vestforbrænding | Denmark |
| 30 | Viborg Fjernvarme | Denmark |
| 31 | Wallenius Water | Sweden |

Work package 2, District Heating Production and System Integration: The hypothesis of this second area is that 4DH has an important role to play in efficient future energy systems. This work package develops energy systems analysis tools, methodologies and theories for the study and scenario-building of future sustainable energy systems with the aim of identifying the role of district heating systems and technologies in various countries.

The European project partners are engaged in the development of EU policies and strategies to define the role of district heating, and similar activities are carried out by the Chinese partner. This includes an investigation of the balance between heat savings and

heat supply as well as the balance between the supplies to individual houses through collective or individual systems, respectively. Moreover, the work package focuses on the development of strategies and software tools for decision-making support to local district heating companies and energy planners.

Work package 3, District Heating Planning and Implementation: This third area focuses on the further development of the planning and management systems based on spatial analysis and geographical information systems (GIS) as a tool for planners and decision-makers. This includes the further advancement of theories and methodologies as well as the design of specific public regulation measures. The latter focuses on how to manage the conflict between implementing energy conservation in buildings and, at the same time, utilising available low-temperature heat sources in district heating, seen from planning, organisational and legal perspectives.

PhD student projects

Thirteen PhD students with their different projects constitute a very vital part of the research centre. Each PhD student will be active during three years before obtaining their PhD degrees. The subjects chosen and appointed PhD students are presented below by their work package affiliation.

WP1: District Heating Grids and Components

1.1 Heating of existing buildings by low-temperature district heating, position not yet filled, DTU-BYG, Lyngby.

1.2 Supply of domestic hot water at comfort temperatures without Legionella, Xiaochen Yang, DTU-BYG, Lyngby.

1.3 Conversion of existing district heating grids to low-temperature operation and extension to new areas of buildings, Soma Mohammadi, AAU-IET, Aalborg.

1.4 Minimising losses in the DH distribution grid, position not yet filled, AAU-IET, Aalborg.

WP2: District Heating Production and System Integration

2.1 Energy Scenarios for Denmark, Rasmus Lund, AAU-CPH, Copenhagen.

2.2 Thermal storage in district heating systems, Sean Bryant, AAU-PLAN, Aalborg.

2.3 Distributed CHP-plants optimized across more electricity markets, Peter Sorknæs, AAU-PLAN, Aalborg.

2.4 Low-temperature energy sources for district heating, Urban Persson, Halmstad University, Sweden.

2.5 The role of district heating in the Chinese energy system, Weiming Xiong, Tsinghua University, Beijing, China

WP3: District Heating Planning and Implementation

3.1 Strategic energy planning in a municipal and legal perspective, Michael Herborn, SDU, Odense.

3.2 Price regulation, tariff models and ownership as elements of strategic energy planning, Søren Djørup, AAU-PLAN, Aalborg.

3.3 Geographical representations of heat demand, efficiency and supply, Position not yet filled, AAU-PLAN, Aalborg.

3.4 Geographical representations of renewable energy systems, Stefan Petrovic, DTU-RISØ, Roskilde.

RESULTS

This paper presents an overview of the progress and results achieved after more than two years of work. These results include the basic 4GDH definition paper, the two Heat Roadmap Europe pre-studies, annual conferences, additional demonstration projects, international PhD courses based on the new international textbook, annual PhD student seminars, and a list of all major papers and articles written so far within the research centre.

Basic 4GDH definition paper

Why should we develop a new generation of district heating technology? Because we need the integration of smart electricity, gas and thermal grids in order to obtain the least cost solution from a combination of renewables and energy efficiency measures in the future energy system. This answer was recently elaborated in the 4GDH definition paper [3], collectively written by senior researchers within the 4DH research centre. The concept of 4th Generation District Heating (4GDH) was defined including the relations to District Cooling and the concepts of Smart Energy and Smart Thermal Grids. The motive was to identify the future challenges of reaching a future renewable non-fossil heat supply as part of the implementation of overall sustainable energy systems.

The basic assumption is that district heating and cooling has an important role to play in future sustainable energy systems - including 100 percent renewable energy systems - but the present generation of district heating and cooling technologies will have to be developed further into a new generation in order to play such a role. Unlike the first three generations, the development of 4GDH involves meeting the challenge of more energy efficient buildings as well as being an integrated part of the operation of smart energy systems, i.e. integration of smart electricity, gas and thermal grids.

Heat Roadmap Europe pre-studies

One early initiative within the 4DH research centre was the Heat Roadmap Europe pre-studies performed together with Euroheat & Power. The main purpose with these European heat market studies was to verify the future long term benefits of district heating, which never had been estimated before. It was also vital for the 4DH research centre to prove that district heating is long term viable within the European Union before elaborating the fourth generation district heating technology.

The benefit of district heating was measured against corresponding scenarios in *Energy Roadmap 2050*,

published by the European Commission in December 2011. This communication report presumed a low market share of 10% for district heating in buildings. We estimated the benefits with higher district heating market share, by assuming it to be 30% in 2030 and 50% in 2050.

The first Heat Roadmap Europe pre-study [4] was published in June 2012. The benefits of district heating were then measured in a business-as-usual scenario. The district heating pathway generated less primary energy use, lower carbon dioxide emissions, additional job creation by investments, and lower total costs for heating European buildings than the Energy Roadmap 2050 scenario. The 2050 cost reduction was estimated to be 14 billion euro. These results were obtained by a novel combination of mapping regional conditions and energy system simulation of the chosen alternatives. The mapping part of the first pre-study was presented at the last International District Heating and Cooling Symposium in Copenhagen [5].

The second Heat Roadmap Europe pre-study [6] was published in May 2013: The benefits of district heating were in this second pre-study measured in an energy efficiency scenario. However, the comparison with the Energy Roadmap 2050 scenario was performed differently. The district heating pathway was designed to give the same primary energy supplies and carbon dioxide emissions as the Energy Roadmap 2050 scenario. The benefit of district heating was then mainly measured as the cost difference. District heating investments replaced then the most expensive end use investments for obtaining higher energy efficiency. More district heating systems became in this case a part of the energy efficiency solution. The 2050 cost reduction was estimated to 100 billion euro, seven times higher than in the business-as-usual scenario. Hereby, we revealed a paradox: District heating has a higher competitiveness in an efficient energy system than in the traditional energy system. A general opinion in the European energy debate is often the opposite.

The results from the Heat Roadmap Europe have been disseminated and communicated in various ways. A scientific summary of the second pre-study has been published in [7]. Numerous presentations of the results have been held in European and various national conferences and seminars. The two pre-studies have also become an essential input to the ongoing discussions about a future heat strategy within European energy policy.

Henrik Lund, the head of the 4DH research centre, has summarised the overall conclusion from the two pre-studies as: **District heating is here to stay, but district heating has to change.**

Annual conferences

Annual 4DH conferences are arranged every year in order to disseminate activities and results from the project. However, the conference perspective changes from year to year. The first conference took place in Aalborg on October 3, 2012, where the initial perspective was to launch and present the new 4DH research centre. The 2013 conference was held in Copenhagen on August 21, and the theme was

'Combined heat and power plants - now and in the future', focusing on the interaction between electricity markets and district heating systems. The third conference in Aalborg is planned for August 18, 2014 with a theme of 'District Heating in Areas with New Buildings'.

Additional demonstration projects

Four working groups have been initiated concerning additional demonstration projects in conjunction to the 4GDH technology. The first working group is about reduced temperature levels in existing district heating systems, the second is about interfaces with electricity markets including heat pumps, the third is about Danish/Chinese collaboration of universities and consultancies, while the fourth working group has a full-scale supply chain (from supply to demand) perspective at national level.

International PhD courses about DHC

Two international PhD courses based on the new international district heating and cooling textbook [8] have been arranged at Halmstad University with Sven Werner as coordinator and main lecturer. They lasted for two weeks with fulltime activities as ordinary lectures associated to the textbook, invited guest lecturers, study visits, daily concluding discussions, and one final examination test.

The first course was held in August 2012 with 36 participants from 12 countries and performed in conjunction with the Swedish Fjärrsyn research program. The gathering basic level of these special district heating courses is presented by the ten exam questions:

| | |
|---|--|
| 1 | Express the fundamental idea of district heating with maximum 12 words! |
| 2 | We have discussed that the overall control system for a whole district heating system is based on four different control systems. Which are the four target purposes for these four control systems? (One answer for each control system) |
| 3 | What is the direct rate of return in percent for an extension of the distribution network, if the linear heat density for the extension is 25 GJ/m, the extension cost is 250 €/m, the current heat price is 14 €/GJ, and the marginal heat supply cost is 9 €/GJ? |
| 4 | Why is normally the district cooling pipe wider than the district heating pipe at the same capacity demand? |
| 5 | What is the specific distribution capital cost for the combination of an investment cost of 300 €/m, an annuity of 8%, and a linear heat density of 12 GJ/m? |
| 6 | A performance indicator for a CHP plant is the power-to-heat ratio. How is it defined? |
| 7 | a) What is the difference between a direct and an indirect connection of the customer space heating circuit in a substation? |

| | |
|----|--|
| | b) What is the difference between an open and a closed connection of the customer domestic hot water circuit in a substation? |
| 8 | Why is a low return temperature preferred in a district heating substation? |
| 9 | Why is a full-loaded wide pipe (large diameter) more cost-effective than a full-loaded narrow pipe (small diameter)? |
| 10 | What was the market share for district heating during 2008 in the heat market for heating buildings within the European Union? |

Some examples of spontaneous course assessments were received in some e-mails arriving after the course:

I would like once again to thank you for an amazing PhD course in Halmstad. I have gained an unforgettable experience about DHC systems. I really appreciate all your efforts, organisation of course structure and study visits.

Thank you for an awesome good course. Made a great difference for me and I feel that many important pieces have found its place.

I want to take advantage of this mail as to thank you again of this excellent PhD course about DHC. For sure, I will promote your "summer university" and also your textbook in COFELY.

Thanks for this very useful course!

Thank you very much for the rewarding course. I learned plenty.

The second course was held in November/December 2013 with 32 participants from 7 countries. The participating PhD students from the 4DH research centre were very active in this course. Almost all PhD students from the large Swedish research program of RESBEE [9] participated also in this second course. This research program is almost completely devoted to the future balance between heat supply and end use energy efficiency in Swedish buildings connected to district heating systems.

PhD student seminars

Internal PhD student seminars have been held at March 7, 2013 and March 13, 2014. In these seminars, the PhD students present their progress and obtained results, and these findings are discussed with the supervisor group and interested participants from the project partners.

List of publications and presentations

The website www.4dh.dk/publications-reports contains currently about ten pages with links to reports, papers, and seminar and conference presentations provided from the project participants, since the start in 2012.

DISCUSSION

District heating is challenged in Europe today with respect to heat supply and heat demands. The current

heat supply from CHP plants based on fossil fuels needs to be replaced by other heat supply in the future. This transition has already started in some places where long term contracts of heat supply from CHP plants have been cancelled for termination within some years. New buildings can nowadays be built with considerable lower heat demands than existing buildings, giving lower heat densities and higher heat distribution costs in the future. Existing buildings are also expected to use less heat in the future.

The 4DH research centre is a good example of how countries can support and facilitate district heating research concerning the transition of the current district heating technology to a new generation of district heating technology, more suitable for the future energy market conditions.

The focus on many PhD students in the research centre will also keep the knowledge gained within universities and the energy system for many years.

OUTLOOK

The first years has been characterised by initiation, recruitments of PhD students, work programs, PhD student courses, and the Heat Roadmap pre-studies. The three ending years will be more focused on results and conclusions concerning the future 4GDH technology with respect to heat distribution, heat supply, and integration into the energy system. Coming results will be presented at the research centre website: www.4dh.dk

The first PhD degree from the 4DH research centre is expected to be obtained by Urban Persson from Halmstad University this coming autumn. The following 2015 and 2016 years will also see further PhD degrees from the rest of the PhD student group.

The research centre has also become an arena for ideas of new international research projects by bringing together researchers will common interests. Participants from the 4DH research centre were active in the European Stratego project application. This project has been granted funding from the IEE 2013 program and will work between 2014 and 2016. This project is planned to contain regional studies of the results obtained in the two Heat Roadmap Europe pre-studies. Several research applications have also been submitted to the 2014 energy efficiency calls within Horizon 2020, the new European framework research program for 2014-2020.

CONCLUSIONS

Two major conclusions can be identified from this early summary of the progress and results from 4DH research centre:

- 4GDH has become a standard label for something new to expect and is used in most discussions about future district heating systems.
- The 4DH research centre has a size beyond the critical mass threshold in order to initiate new sustainable ideas. This is especially valid concerning the mixture of very curious PhD

students and more experienced senior researchers.

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