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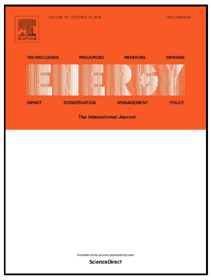
Published in:
Energy

DOI (link to publication from Publisher):
10.1016/j.energy.2018.09.115

Publication date:
2018

Document Version
Accepted author manuscript, peer reviewed version

Accepted Manuscript



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PII:	S0360-5442(18)31879-6
DOI:	10.1016/j.energy.2018.09.115
Reference:	EGY 13809
To appear in:	*Energy*
Received Date:	13 July 2018
Accepted Date:	17 September 2018

Please cite this article as: Henrik Lund, Neven Duic, Poul Alberg Østergaard, Brian Vad Mathiesen, Future District Heating Systems and Technologies: On the role of Smart Energy Systems and 4^{th} Generation District Heating, *Energy* (2018), doi: 10.1016/j.energy.2018.09.115

Version R1 Marked-Up-Manuscript: 6 September 2018

Perspective:

Future District Heating Systems and Technologies: On the role of Smart Energy Systems and 4th Generation District Heating

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Abstract

This paper provides a perspective on the development of future district heating systems and technologies and their role in future smart energy systems. The reviewed papers elaborate on or otherwise contribute to the theoretical scientific understanding of how we can design and implement a suitable and least-cost transformation into a sustainable energy future. Focus is on the important role of the next generation of district heating and cooling technologies. The status of the scientific contributions demonstrates a high level of understanding of how to deal with the technical aspects. The primary current challenge seems to be the understanding of the implementation of these.

Keywords: Smart Energy Systems, District Heating, District Cooling, Sustainable Energy, Renewable Energy.

1. Introduction

The analysis and planning of a world-wide transition towards an environmentally benign energy system are steadily gaining importance as the world faces difficulties in reaching the modest Paris goals for climate change mitigation. One area that has gained attention over the years is the heating sector and its integration into future smart energy systems. This is for instance the topic of a series of conferences titled *International Conference on Smart Energy Systems and 4th Generation District Heating* that has become an annual event in Denmark.

Globally, the current position of district heating and cooling shows how these technologies have strong potentials for being viable heating and cooling supply options in a future world. However, more efforts are required for the identification, assessment, and implementation of these potentials with the aim to harvest the global benefits of district heating and cooling [1].

The development of 4th generation district heating (4GDH) [2] is essential to the implementation of Smart Energy Systems to fulfil national objectives of future low-carbon strategies[3]. With lower and more flexible distribution temperatures, 4th generation district heating can utilise renewable energy sources while meeting the requirements of low-energy buildings and energy conservation measures in the existing building stock[4]. Moreover, the concept of future district heating is closely connected to the potential for utilizing district cooling benefits [5].

The concept of Smart Energy Systems emphasizes the importance of applying a coherent and cross-sectoral approach to finding the best solutions and how this also calls for the active inclusion of the heating and cooling sectors. The Smart Energy Systems concept is essential for 100% renewable energy systems to harvest storage synergies across energy sub-sectors and exploit low-value heat sources [6–8]. Also, as stressed in[9], the sectorial integration into smart energy systems enables the exploration of low-cost storage options, thus facilitating the integration of fluctuating renewable energy sources.

The Smart Energy System concept represents a scientific shift in paradigms away from single-sector thinking to a coherent energy systems understanding of how to benefit from the integration of all sectors and infrastructures including future 4th generation district heating and cooling solutions [10–12]. It is also a concept that transcends technical systems and calls for integrated coordination with governance systems[13] and ownership structures [14,15].

This perspective paper provides a status of current research with a view to identifying future research directions within the field. The starting point is mainly papers from the *3rd International Conference on Smart Energy Systems and 4th Generation District Heating,* but the paper also extends beyond this conference. The status is structured in five sections on Transformation studies; Operation of district heating (DH) grids; 4DGH and building systems; 4GDH and waste heat sources, and District heating for balancing fluctuating renewables. Finally, section 7 creates an overview of further perspectives.

2. Transformation studies

This perspective paper starts with four papers regarding the transformation of current systems into future 4th generation district heating solutions with a focus on the district heating grid. These papers add to previous Smart Energy Systems and 4th Generation District Heating research[4,16,25–28,17–24] by having a focus on transformation processes into low-temperature district heating both in the north and in the south.

In *Methodology for evaluating the transition process dynamics towards 4th generation district heating systems* [29], Volkova et al. review the barriers faced by existing district heating systems over the course of the transition process towards the 4th generation. Using a large-scale District Heating system in Tallinn (Estonia) as a case, supply and return temperatures, the share of renewable energy, and network conditions demonstrated the highest potential for improvement and had the most notable impact on the transition process.

In the paper *Pathway and Restriction in District Heating Systems Development Towards 4th Generation District Heating* [30], Ziemele et al. analyse the indicators that describe the overall efficiency of the district heating system and restrictions for its transition towards a 4th generation district heating system using the case of Latvia.

In *Challenges and potentials for low-temperature district heating implementation in Norway* [31], Nord et al. analyse the challenges in the transition to low-temperature district heating (LTDH) and estimate the increased competitiveness in low heat density areas using Trondheim in Norway as a case.

In the paper *Technical and economic feasibility of sustainable heating and cooling supply options in southern European municipalities - A case study for Matosinhos, Portugal* [32], Popovski et al. add to the abovementioned research of northern systems to a system located in the south in which district cooling is also relevant. The focus is to assess the cost-effectiveness of sustainable heat and cooling supply solutions under southern European conditions.

Knies[33] investigates means for assessing appropriate heating supply systems in *A spatial approach for future-oriented heat planning in urban areas* and develops a framework for performing integrated energy planning for local areas.

3. Operation of DH grids

From looking at the transformation into 4th generation in the previous papers, the next papers take a focus on the operation of district heating grids and add to previous work with a similar focus [34–38].

In *Balancing Demand and Supply: Linking Neighborhood-level Building Load Calculations with Detailed District Energy Network Analysis Models* [39], Letellier-Duchesne et al. describe a modelling workflow based on a new Rhinoceros-based plugin that combines an urban building energy model with a network topology optimization and a heat generation scenario model, thus bridging the gap between the planning phase and the design phase.

Suryanarayana et al. address the issue of forecasting methods for heat load forecasting of district heating networks and presents two methods that gain significant improvements compared to the previous works in their paper *Thermal load forecasting in district heating networks using deep learning and advanced feature selection methods* [40].

Kauko et al. apply dynamic modelling to study the technical, energy and environmental impacts of including prosumers - customers who both consume and produce heat - in a local low-temperature DH grid in *Dynamic modelling of local district heating grids with prosumers: A case study for Norway* [41].

In *A Theoretical Benchmark for Bypass Controllers in a Residential District Heating Network* [42], Vandermeulen et al. compare two commonly used control strategies (manual control and thermostatic control) to a new theoretical benchmark that provides an upper boundary for the performance of bypass controllers. This theoretical benchmark ensures a just-in-time delivery of warm water by taking into account time delays in the network.

In *Technical Assessment of Electric Heat Boosters in Low-Temperature District Heating based on Combined Heat and Power Analysis* [43], Cai et al. provide a technical assessment of electric heat boosters (EHBs) in low-energy districts and demonstrate that lower supply temperatures and intelligent components can improve system efficiency and turn the district heating network into an integrated part of sustainable energy systems.

In *Improving the performance of booster heat pumps using zeotropic Mixtures* [44], Zühlsdorf et al. demonstrate an increase in the thermodynamic performance of a booster heat pump, which was achieved by choosing the working fluid among pure and mixed fluids. The booster heat pump was integrated in an ultra-low-temperature district heating network with a forward temperature of 40 °C to produce domestic hot water by heating part of the forward stream to 60 °C, while cooling the remaining part to the return temperature of 25 °C. Previous work has also established positive effects on DH temperature levels and thus positive system effects of booster heat pumps. This includes Zvingilaite et al.'s *Low temperature DH consumer unit with micro heat pump for DHW preparation* [45] and Østergaard and Andersen's two articles *Booster heat pumps and central heat pumps in district heating* [46] and *Economic feasibility of booster heat pumps in heat pump-based district heating systems* [47].

Best investigates the implication of temperature levels on district heating in systems in *Economic comparison of low-temperature and ultra-low-temperature district heating for new building developments with low heat demand densities in Germany*[48] describing how pipe flows, pumping and diameters (and thus investments) differ with temperature levels. Also with a close grid perspective, Schuchardt [49] investigates methods for assessing losses from district heating pipes.

4. 4GDH and building systems

From looking at the temperatures in the district heating grid in the previous section, this section adds to previous research [50–52] by taking a focus on the buildings including the radiators in the buildings.

In [53], Andric et al. evaluate the impact of global warming and building renovation measures on techno-economic parameters of district heating systems. Based on the case of St. Félix in France, results indicate that the decrease of heat demand proved to be most extensive after the first year of renovation (2020), decreasing by 52% compared to the reference value (2010).

Ashfaq and Ianakiev investigate the hydraulic balance of the heating network as a pre-condition for the implementation of a low-temperature district heating (LTDH) network in *Investigation of hydraulic imbalance for converting existing boiler based buildings to low temperature district heating* [54]. Results show that the hydraulic imbalance is due to the absence of flow-limiters and balancing valves on the return pipe, and thermostatic radiator valves alone are unable to maintain the hydraulic balance in the heating network.

Schweiger et al. present a comprehensive comparison of so-called "multi-domain - open - general tools" (TRNSYS, Matlab Simulink, IDA ICE, Modelica), including buildings, HVAC systems, district heating and cooling systems and power distribution systems in *District energy systems:*

Modelling paradigms and general-purpose tools [55]. One main conclusion is that object-oriented acausal modelling approaches allow rapid prototyping. While this approach is widely applied to limited problems, applications to large-scale and complex problems are still missing.

In *Solar facade module for nearly zero energy building* [56], Vanaga et al. address the topic of nearly zero energy buildings as efficiency measures including the utilisation of solar energy. Results show that the dynamics of heat flows and accumulation processes in the facade module are very complex due to highly changing outdoor and indoor conditions.

In *Multi-objective optimization algorithm coupled to EnergyPLAN software: the EPLANopt model* [57], Prina et al. present the model EPLANopt, developed by Eurac Research, based on the deterministic simulation model EnergyPLAN[58,59] developed at Aalborg University coupled with a Multi-Objective Evolutionary Algorithm built on the Python library DEAP. In the test, particular attention is given to the analysis of energy efficiency of buildings. A curve representing the marginal costs of the different energy efficiency strategies versus the annual energy saving is applied to the model through an external Python script. Here the authors expand on previous optimization work by Mahbub et al.[60]

De Jaeger et al. present and develop GIS methodologies and tools to assess the feasibility of district energy systems as well as to design them in an optimal way in *Impact of Building Geometry Description within District Energy Simulations* [61]. It is concluded that GIS contain a significant amount of useful data, but the error that results from the deployed level of detail must be kept in mind when assessing the simulation results.

5. 4GDH and waste heat sources

Lower temperatures are key characteristics of 4GDH systems – not least due to the improved possibilities of exploiting waste heat sources. This section explores contemporary work on the use of industrial excess heat and solar power in district heating grids and systems emphasising the importance of low-temperature grids as well as the use of large-scale thermal storage. The contemporary work adds to previous work with the same focus [62–66]; however, here we focus on the use of solar thermal [67–69] including the use of Organic Rankine Cycle technologies [70,71].

In *Risk assessment of industrial excess heat recovery in district heating systems* [72], Lygnerud and Werner address the recovery of industrial excess heat for use in district heating systems and conclude that only a small proportion of industrial heat recovery has been lost in Sweden because of terminated industrial activities. The risk premium of losing industrial heat recovery for this specific reason should be considered as being lower than often presumed in feasibility studies.

In *Spatiotemporal and economic analysis of industrial excess heat as a resource for district heating* [73], Bühler et al. show that the temporal mismatch between excess heat and district heating demand and lack of demand, reduces the theoretical substitution potential by almost 30%. If heat storages are introduced, the total potential is reduced by only 10%.

Köfinger et al. show that a strategic operation of the seasonal storage could increase the number of charging cycles and thereby increase significantly the revenues of the system in *Simulation-based evaluation of large scale waste heat utilization in urban district heating networks: Optimized integration and operation of a seasonal storage* [74]. This is mainly due to the combined utilization of the storage in a seasonal approach to shift the waste heat from the summer to the winter period and use it as a short-term buffer.

In *Cost-benefit analysis of district heating systems using heat from nuclear plants in seven European countries* [75], Leurent et al. evaluate and compare the potential cost savings and greenhouse gas (GHG) reduction of district heating (DH) systems using heat from nuclear combined heat and power plants (NCHP) in Europe and identify a large potential for extending DH networks for France and the United Kingdom despite the expected decrease in the heat demand due to building renovation.

Pakere et al. compare several different scenarios for solar system design and identify different strengths and weaknesses in *Solar power and heat production via photovoltaic thermal panels for district heating and industrial plant* [76].

In *Multi-criteria analysis of storages integration and operation solutions into the district heating network of Aarhus - a Simulation Case Study* [77], Marguerite and Andresen assess possibilities of integration of centralised and decentralised storages in a district heating network with the objective to smooth the heat demand during peak hours (Peak-based strategy) or to reduce the operational costs of the DHN (Price-based strategy).

6. District heating for balancing fluctuating renewables

Integration between sectors enables the utilisation of low-cost storage systems to balance fluctuating renewable electricity generation as explored by Lund et al.[9] The following papers focus on the potentials for using district heating systems in the balancing of renewable energy in the electricity grid. Contributions in previous 4GDH and smart energy system work have addressed the combination of CHP and heat pumps [78] and power-to-heat [79]. In the following, the focus is more on market design and integration.

In *The Electricity Market in a Renewable Energy System* [80], Djørup et al- investigate the effects of a cross-sectoral smart energy system concept on cost structures on electricity markets. It is concluded that the current electricity market structure is not able to financially sustain the amounts of wind power necessary for the transition to a 100% renewable energy system.

Sneum and Sandberg also approach the integration issue from an economic perspective in their article on *Economic incentives for flexible district heating in the Nordic countries*[81] finding among others that heat storage is a *"no-regrets solution"*.

Pablo et al. investigate the optimal operation of cogeneration plants combined with thermal storage in *The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system* [82]. The analysis indicates that the utilisation of CHP plants improves global efficiency and reduces the total cost of the system. Additionally, thermal storage increases the penetration of renewable energy.

Meesenburg et al. present a method to assess the impact of providing demand flexibility on the performance of the conversion system based on a dynamic exergoeconomic analysis in *Dynamic exergoeconomic analysis of a heat pump system used for ancillary services in an integrated energy* *system* [83]. It is found that providing demand flexibility causes higher exergy destruction, mainly due to heat losses during storage and the need to reheat the fluid using an electric heater.

In *Recycling construction and industrial landfill waste material for backfill in horizontal ground heat exchanger systems* [84], Al-Ameen and Evans compare the temperature distribution development in different backfill materials. The tested materials include sand, basalt, brick, concrete, and metallic by-products including copper slag, aluminium slag, mill scale and iron ores. Results obtained from both experimental and numerical studies show that mill scale, copper slag and aluminium slag were the best backfill materials, where the thermal capacity of the horizontal ground heat exchangers (HGHE) system can be doubled.

Finally, one paper addresses the importance of research within district heating in general. In *Synthesis of Recent Swedish District Heating Research* [85], Sernhed et al perform a synthesis on the Swedish research frontier by assessing these recent research projects and define three future challenges for the Swedish district heating industry: future strategies to communicate the value of district heating, a vision for district heating beyond the transition to fossil free supply, and technology development for the efficient use of low-temperature heat sources.

7. Further perspectives

This paper has highlighted a number of contributions elaborating on or otherwise contributing to the theoretical scientific understanding of the development and design of future district heating systems and technologies.

The highlights demonstrate how a transformation into low-temperature becomes essential for the technology to play its role in the future. A closer look on the use of industrial excess heat and solar power in district heating grids and systems emphasise the importance of low-temperature grids as well as the use of large-scale thermal storage. It is also highlighted how such a transformation calls for improvements in the operation of district heating grids as well as in the heating systems in the individual buildings. However, substantial benefits can be achieved in terms of lowering the grid losses, utilising more excess heat as well as using district heating systems in the balancing of renewable energy in the electricity grid.

Globally, district heating and cooling have a strong technical and economic potential, and represent a viable future heating and cooling supply option. However, more efforts are required for the identification, assessment, and implementation of these potentials with the aim to harvest the global benefits of district heating and cooling.

The status of the scientific contributions demonstrates a high level of understanding of how to deal with the technical aspects. The primary current challenge seems to be the understanding of the implementation, in which a local understanding of the concrete conditions as well as the legal framework is needed.

Acknowledgments

This perspective papers takes its point of departure in the 3rd International Conference on Smart Energy Systems and 4th Generation District Heating (SES4DH 2017) which was held at the National Museum in Copenhagen, Denmark on 12-13 September 2017 with 350 participants. The conference included more than 150 presentations with industrial and scientific inputs from 25 different countries resulting in a programme of large variety and many interesting sessions. See also [86].

Main part of the work presented in this perspective paper is a result of the research activities of the Strategic Research Centre for 4th Generation District Heating (4DH) (grant number 0603-00498B) and the RE-INVEST project (grant number 6154-00022B), which both have received funding from Innovation Fund Denmark.

References

[1] Werner S. International review of district heating and cooling. Energy 2017. doi:10.1016/j.energy.2017.04.045.

[2] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. doi:10.1016/j.energy.2014.02.089.

[3] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, et al. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

[4] Lund R, Østergaard DS, Yang X, Mathiesen BV. Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective. Int J Sustain Energy Plan Manag 2017;12:5–18. doi:10.5278/ijsepm.2017.12.2.

[5] Werner S. District heating and cooling in Sweden. Energy 2017;126:419–29. doi:10.1016/j.energy.2017.03.052.

[6] Lund H. Renewable Energy Systems - A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions. 2nd ed. Academic Press; 2014.

[7] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems - A market operation based approach and understanding. Energy 2012;42:96–102. doi:10.1016/j.energy.2012.04.003.

[8] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016;11. doi:10.5278/ijsepm.2016.11.2.

[9] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy Storage and Smart Energy Systems. Int J Sustain Energy Plan Manag 2016;11:3–14.

doi:10.5278/ijsepm.2016.11.2.

[10] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017. doi:10.1016/j.energy.2017.05.123.

[11] Werner S. European space cooling demands. Energy 2015. doi:10.1016/j.energy.2015.11.028.

[12] Lund H, Vad Mathiesen B, Connolly D, Østergaarda PA. Renewable energy systems - A smart energy systems approach to the choice and modelling of 100 % renewable solutions. vol. 39. 2014. doi:10.3303/CET1439001.

[13] Hvelplund F, Djørup S. Multilevel policies for radical transition: Governance for a 100% renewable energy system. Environ Plan C Polit Sp 2017;35:1218–41. doi:10.1177/2399654417710024.

[14] Hvelplund F, Möller B, Sperling K. Local ownership, smart energy systems and better wind power economy. Energy Strateg Rev 2013;1:164–70. doi:10.1016/j.esr.2013.02.001.

[15] Hvelplund F, Østergaard PA, Meyer NI. Incentives and barriers for wind power expansion and system integration in Denmark. Energy Policy 2017;107. doi:10.1016/j.enpol.2017.05.009.

[16] Ziemele J, Gravelsins A, Blumberga A, Blumberga D. Combining energy efficiency at source and at consumer to reach 4th generation district heating: Economic and system dynamics analysis. Energy 2017. doi:10.1016/j.energy.2017.04.123.

[17] Prasanna A, Dorer V, Vetterli N. Optimisation of a district energy system with a low temperature network. Energy 2017. doi:10.1016/j.energy.2017.03.137.

[18] Brange L, Lauenburg P, Sernhed K, Thern M. Bottlenecks in district heating networks and how to eliminate them – A simulation and cost study. Energy 2017. doi:10.1016/j.energy.2017.04.097.

[19] Schweiger G, Larsson P-O, Magnusson F, Lauenburg P, Velut S. District heating and cooling systems – Framework for Modelica-based simulation and dynamic optimization. Energy 2017. doi:10.1016/j.energy.2017.05.115.

[20] Kauko H, Kvalsvik KH, Rohde D, Hafner A, Nord N. Dynamic modelling of local low-temperature heating grids: A case study for Norway. Energy 2017. doi:10.1016/j.energy.2017.07.086.

[21] Ommen T, Thorsen JE, Markussen WB, Elmegaard B. Performance of ultra low temperature district heating systems with utility plant and booster heat pumps. Energy 2017. doi:10.1016/j.energy.2017.05.165.

[22] Nastasi B, Lo Basso G. Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems. Energy 2016;110:5–22. doi:10.1016/j.energy.2016.03.097.

[23] Schüwer D, Krüger C, Merten F, Nebel A. The potential of grid-orientated distributed

cogeneration on the minutes reserve market and how changing the operating mode impacts on CO2 emissions. Energy 2016. doi:10.1016/j.energy.2016.02.108.

[24] Lythcke-Jørgensen C, Ensinas AV, Münster M, Haglind F. A methodology for designing flexible multi-generation systems. Energy 2016. doi:10.1016/j.energy.2016.01.084.

[25] Xiong W, Wang Y, Mathiesen BV, Zhang X. Case study of the constraints and potential contributions regarding wind curtailment in Northeast China. Energy 2016. doi:10.1016/j.energy.2016.03.093.

[26] Prina MG, Cozzini M, Garegnani G, Moser D, Oberegger UF, Vaccaro R, et al. Smart energy systems applied at urban level: the case of the municipality of Bressanone-Brixen. Int J Sustain Energy Plan Manag 2016;10. doi:10.5278/ijsepm.2016.10.3.

[27] Leeuwen RP van, Wit JB de, Smit GJM. Energy scheduling model to optimize transition routes towards 100% renewable urban districts. Int J Sustain Energy Plan Manag 2017;13. doi:10.5278/ijsepm.2017.13.3.

[28] Sernhed K, Gåverud H, Sandgren A. Costumer perspectives on district heating price models. Int J Sustain Energy Plan Manag 2017;13. doi:10.5278/ijsepm.2017.13.4.

[29] Volkova A, Mašatin V, Siirde A. Methodology for evaluating the transition process dynamics towards 4th generation district heating networks. Energy 2018;150:253–61. doi:10.1016/J.ENERGY.2018.02.123.

[30] Ziemele J, Cilinskis E, Blumberga D. Pathway and restriction in district heating systems development towards 4th generation district heating. Energy 2018;152:108–18. doi:10.1016/J.ENERGY.2018.03.122.

[31] Nord N, Løve Nielsen EK, Kauko H, Tereshchenko T. Challenges and potentials for low-temperature district heating implementation in Norway. Energy 2018;151:889–902. doi:10.1016/J.ENERGY.2018.03.094.

[32] Popovski E, Fleiter T, Santos H, Leal V, Fernandes EO. Technical and economic feasibility of sustainable heating and cooling supply options in southern European municipalities-A case study for Matosinhos, Portugal. Energy 2018;153:311–23. doi:10.1016/J.ENERGY.2018.04.036.

[33] Knies J. A spatial approach for future-oriented heat planning in urban areas. Int J Sustain Energy Plan Manag 2018. doi:10.5278/ijsepm.2018.16.2.

[34] Ziemele J, Gravelsins A, Blumberga A, Vigants G, Blumberga D. System dynamics model analysis of pathway to 4th generation district heating in Latvia. Energy 2015. doi:10.1016/j.energy.2015.11.073.

[35] Köfinger M, Basciotti D, Schmidt RR, Meissner E, Doczekal C, Giovannini A. Low temperature district heating in Austria: Energetic, ecologic and economic comparison of four case studies. Energy 2016. doi:10.1016/j.energy.2015.12.103.

[36] Büchele R, Kranzl L, Müller A, Hummel M, Hartner M, Deng Y, et al. Comprehensive Assessment of the Potential for Efficient District Heating and Cooling and for High-Efficient Cogeneration in Austria. Int J Sustain Energy Plan Manag 2016. doi:10.5278/ijsepm.2016.10.2.

[37] Trømborg E, Havskjold M, Bolkesjø TF, Kirkerud JG, Tveten ÅG. Flexible use of electricity in heat-only district heating plants. Int J Sustain Energy Plan Manag 2017;12:29–46. doi:10.5278/ijsepm.2017.12.4.

[38] Flores JFC, Espagnet AR, Chiu JN, Martin V, Lacarrière B. Techno-Economic Assessment of Active Latent Heat Thermal Energy Storage Systems with Low-Temperature District Heating. Int J Sustain Energy Plan Manag 2017;13. doi:10.5278/ijsepm.2017.13.2.

[39] Letellier-Duchesne S, Nagpal S, Kummert M, Reinhart C. Balancing demand and supply: Linking neighborhood-level building load calculations with detailed district energy network analysis models. Energy 2018;150:913–25. doi:10.1016/J.ENERGY.2018.02.138.

[40] Suryanarayana G, Lago J, Geysen D, Aleksiejuk P, Johansson C. Thermal load forecasting in district heating networks using deep learning and advanced feature selection methods. Energy 2018. doi:10.1016/j.energy.2018.05.111.

[41] Kauko H, Kvalsvik KH, Rohde D, Nord N, Utne Å. Dynamic modeling of local district heating grids with prosumers: A case study for Norway. Energy 2018;151:261–71. doi:10.1016/J.ENERGY.2018.03.033.

[42] Vandermeulen A, van der Heijde B, Patteeuw D, Vanhoudt D, Helsen L. A theoretical benchmark for bypass controllers in a residential district heating network. Energy 2018;151:45–53. doi:10.1016/J.ENERGY.2018.02.156.

[43] Cai H, You S, Wang J, Bindner HW, Klyapovskiy S. Technical assessment of electric heat boosters in low-temperature district heating based on combined heat and power analysis. Energy 2018;150:938–49. doi:10.1016/J.ENERGY.2018.02.084.

[44] Zühlsdorf B, Meesenburg W, Ommen TS, Thorsen JE, Markussen WB, Elmegaard B. Improving the performance of booster heat pumps using zeotropic mixtures. Energy 2018;154:390–402. doi:10.1016/J.ENERGY.2018.04.137.

[45] Zvingilaite E, Ommen T, Elmegaard B, Franck ML. Low temperature DH consumer unit with micro heat pump for DHW preparation. Proc. 13th Int. Symp. Dist. Heat. Cool., District Energy Development Center; 2012, p. 136–43.

[46] Østergaard PA, Andersen AN. Booster heat pumps and central heat pumps in district heating. Appl Energy 2016;184:1374–88. doi:10.1016/j.apenergy.2016.02.144.

[47] Østergaard PA, Andersen AN. Economic feasibility of booster heat pumps in heat pump-based district heating systems. Energy 2018;155:921–9. doi:10.1016/J.ENERGY.2018.05.076.

[48] Best I, Orozaliev J, Vajen K. Economic comparison of low-temperature and ultra-low-temperature district heating for new building developments with low heat demand

densities in Germany. Int J Sustain Energy Plan Manag 2018;16. doi:10.5278/ijsepm.2018.16.4.

[49] Schuchardt GK, Kraft S, Narften M, Bagusche O. Development of an empirical method for determination of thermal conductivity and heat loss for pre-insulated plastic bonded twin pipe systems. Int J Sustain Energy Plan Manag 2018;16. doi:10.5278/ijsepm.2018.16.5.

[50] Jangsten M, Kensby J, Dalenbäck J-O, Trüschel A. Survey Of Radiator Temperatures In Buildings Supplied By District Heating. Energy 2017. doi:10.1016/j.energy.2017.07.017.

[51] Yang X, Li H, Svendsen S. Decentralized substations for low-temperature district heating with no Legionella risk, and low return temperatures. Energy 2016. doi:10.1016/j.energy.2015.12.073.

[52] Østergaard DS, Svendsen S. Replacing critical radiators to increase the potential to use low-temperature district heating – A case study of 4 Danish single-family houses from the 1930s. Energy 2016. doi:10.1016/j.energy.2016.03.140.

[53] Andrić I, Fournier J, Lacarrière B, Le Corre O, Ferrão P. The impact of global warming and building renovation measures on district heating system techno-economic parameters. Energy 2018;150:926–37. doi:10.1016/J.ENERGY.2018.03.027.

[54] Ashfaq A, Ianakiev A. Investigation of hydraulic imbalance for converting existing boiler based buildings to low temperature district heating. Energy 2018;160:200–12. doi:10.1016/J.ENERGY.2018.07.001.

[55] Schweiger G, Heimrath R, Falay B, O'Donovan K, Nageler P, Pertschy R, et al. District energy systems: Modelling paradigms and general-purpose tools. Energy 2018. doi:10.1016/J.ENERGY.2018.08.193.

[56] Vanaga R, Blumberga A, Freimanis R, Mols T, Blumberga D. Solar facade module for nearly zero energy building. Energy 2018. doi:10.1016/J.ENERGY.2018.04.167.

[57] Prina MG, Cozzini M, Garegnani G, Manzolini G, Moser D, Filippi Oberegger U, et al. Multi-objective optimization algorithm coupled to EnergyPLAN software: The EPLANopt model. Energy 2018;149:213–21. doi:10.1016/J.ENERGY.2018.02.050.

[58] Lund H, Münster E. Management of surplus electricity-production from a fluctuating renewable-energy source. Appl Energy 2003;76. doi:10.1016/S0306-2619(03)00048-5.

[59] Østergaard PA. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy 2015;154:921–33. doi:10.1016/j.apenergy.2015.05.086.

[60] Mahbub MS, Cozzini M, Østergaard PA, Alberti F. Combining multi-objective evolutionary algorithms and descriptive analytical modelling in energy scenario design. Appl Energy 2016;164. doi:10.1016/j.apenergy.2015.11.042.

[61] De Jaeger I, Reynders G, Ma Y, Saelens D. Impact of building geometry description within

district energy simulations. Energy 2018;158:1060–9. doi:10.1016/J.ENERGY.2018.06.098.

[62] Kalina J. Complex thermal energy conversion systems for efficient use of locally available biomass. Energy 2016. doi:10.1016/j.energy.2016.02.164.

[63] Persson U, Münster M. Current and future prospects for heat recovery from waste in European district heating systems: A literature and data review. Energy 2016. doi:10.1016/j.energy.2015.12.074.

[64] Lund R, Persson U. Mapping of potential heat sources for heat pumps for district heating in Denmark. Energy 2016. doi:10.1016/j.energy.2015.12.127.

[65] Chiu JN, Castro Flores J, Martin V, Lacarrière B. Industrial surplus heat transportation for use in district heating. Energy 2016. doi:10.1016/j.energy.2016.05.003.

[66] Stennikov VA, Iakimetc EE. Optimal planning of heat supply systems in urban areas. Energy 2016. doi:10.1016/j.energy.2016.02.060.

[67] Rämä M, Mohammadi S. Comparison of distributed and centralised integration of solar heat in a district heating system. Energy 2017. doi:10.1016/j.energy.2017.03.115.

[68] Soloha R, Pakere I, Blumberga D. Solar energy use in district heating systems. A case study in Latvia. Energy 2017. doi:10.1016/j.energy.2017.04.151.

[69] Winterscheid C, Dalenbäck J-O, Holler S. Integration of solar thermal systems in existing district heating systems. Energy 2017. doi:10.1016/j.energy.2017.04.159.

[70] Kaczmarczyk TZ, Żywica G, Ihnatowicz E. The impact of changes in the geometry of a radial microturbine stage on the efficiency of the micro CHP plant based on ORC. Energy 2017. doi:10.1016/j.energy.2017.05.166.

[71] Wahlroos M, Syri S, Pärssinen M, Manner J. Utilizing data center waste heat in district heating – impacts on energy efficiency and prospects for low-temperature district heating networks. Energy 2017. doi:10.1016/j.energy.2017.08.078.

[72] Lygnerud K, Werner S. Risk assessment of industrial excess heat recovery in district heating systems. Energy 2018;151:430–41. doi:10.1016/J.ENERGY.2018.03.047.

[73] Bühler F, Petrović S, Holm FM, Karlsson K, Elmegaard B. Spatiotemporal and economic analysis of industrial excess heat as a resource for district heating. Energy 2018;151:715–28. doi:10.1016/J.ENERGY.2018.03.059.

[74] Köfinger M, Schmidt RR, Basciotti D, O.Terreros, Baldvinsson I, Mayrhofer J, et al. Simulation based evaluation of large scale waste heat utilization in urban district heating networks: Optimized integration and operation of a seasonal storage. Energy 2018. doi:10.1016/J.ENERGY.2018.06.192.

[75] Leurent M, Da Costa P, Rämä M, Persson U, Jasserand F. Cost-benefit analysis of district heating systems using heat from nuclear plants in seven European countries. Energy 2018;149:454–72. doi:10.1016/J.ENERGY.2018.01.149.

[76] Pakere I, Lauka D, Blumberga D. Solar power and heat production via photovoltaic thermal panels for district heating and industrial plant. Energy 2018;154:424–32. doi:10.1016/J.ENERGY.2018.04.138.

[77] Marguerite C, Andresen GB, Dahl M. Multi-criteria analysis of storages integration and operation solutions into the district heating network of Aarhus – A simulation case study. Energy 2018;158:81–8. doi:10.1016/J.ENERGY.2018.06.013.

[78] Levihn F. CHP and heat pumps to balance renewable power production: Lessons from the district heating network in Stockholm. Energy 2017. doi:10.1016/j.energy.2017.01.118.

[79] Schweiger G, Rantzer J, Ericsson K, Lauenburg P. The potential of power-to-heat in Swedish district heating systems. Energy 2017. doi:10.1016/j.energy.2017.02.075.

[80] Djørup S, Thellufsen JZ, Sorknæs P. The electricity market in a renewable energy system. Energy 2018;162:148–57. doi:10.1016/J.ENERGY.2018.07.100.

[81] Sneum DM, Sandberg E. Economic incentives for flexible district heating in the Nordic countries. Int J Sustain Energy Plan Manag 2018;16. doi:10.5278/ijsepm.2018.16.3.

[82] Jiménez Navarro JP, Kavvadias KC, Quoilin S, Zucker A. The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system. Energy 2018;149:535–49. doi:10.1016/J.ENERGY.2018.02.025.

[83] Meesenburg W, Ommen T, Elmegaard B. Dynamic exergoeconomic analysis of a heat pump system used for ancillary services in an integrated energy system. Energy 2018;152:154–65. doi:10.1016/J.ENERGY.2018.03.093.

[84] Al-Ameen Y, Ianakiev A, Evans R. Recycling construction and industrial landfill waste material for backfill in horizontal ground heat exchanger systems. Energy 2018;151:556–68. doi:10.1016/J.ENERGY.2018.03.095.

[85] Sernhed K, Lygnerud K, Werner S. Synthesis of recent Swedish district heating research. Energy 2018;151:126–32. doi:10.1016/J.ENERGY.2018.03.028.

[86] Østergaard PA, Lund H, Mathiesen BV. Editorial - Smart energy systems and 4th generation district heating systems. Int J Sustain Energy Plan Manag 2018;16:1–2. doi:10.5278/ijsepm.2018.16.1.

Highlights:

- a transformation into low-temperature becomes essential for future district heating
- high level of understanding of how to deal with the technical aspects
- primary current challenge seems to be the understanding of the implementation