

Using residential buildings to manage flexibility in the district heating network

Perspectives and future visions from sector professionals

Andersen, Pernille Viktoria Kathja; Georg, Susse; Gram-Hanssen, Kirsten; Heiselberg, Per; Horsbøl, Anders; Johansen, Katinka; Johra, Hicham; Marszal-Pomianowska, Anna; Møller, Emil Styrbæk

Published in:

1st Nordic conference on Zero Emission and Plus Energy Buildings

DOI (link to publication from Publisher):

[10.1088/1755-1315/352/1/012032](https://doi.org/10.1088/1755-1315/352/1/012032)

Creative Commons License

Unspecified

Publication date:

2019

Document Version

Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Andersen, P. V. K., Georg, S., Gram-Hanssen, K., Heiselberg, P., Horsbøl, A., Johansen, K., Johra, H., Marszal-Pomianowska, A., & Møller, E. S. (2019). Using residential buildings to manage flexibility in the district heating network: Perspectives and future visions from sector professionals. In *1st Nordic conference on Zero Emission and Plus Energy Buildings* (1 ed., Vol. 352, pp. 1-9). Article 012032 IOP Publishing. <https://doi.org/10.1088/1755-1315/352/1/012032>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

PAPER • OPEN ACCESS

Using residential buildings to manage flexibility in the district heating network: perspectives and future visions from sector professionals

To cite this article: P V K Andersen *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **352** 012032

View the [article online](#) for updates and enhancements.

Using residential buildings to manage flexibility in the district heating network: perspectives and future visions from sector professionals

P V K Andersen¹, S Georg², K Gram-Hanssen³, P K Heiselberg⁴, A Horsbøl¹, K Johansen³, H Johra⁴, A Marszal-Pomianowska⁴ and E S Møller¹

¹ Department of Communication and Psychology, Aalborg University, Rendsburggade 14, DK-9000 Aalborg Øst, Denmark

² Department of Planning, Aalborg University, A.C. Meyers Vænge 15, 2450 Copenhagen SV, Denmark

³ Danish Building Research Institute, Aalborg University, A.C. Meyers Vænge 15, 2450 København SV, Denmark

⁴ Department of Civil Engineering, Aalborg University, Thomas Manns Vej 23, DK-9220, Aalborg Øst, Denmark

Corresponding author: Katinka Johansen, kaj@sbi.aau.dk

Abstract. Intermittent energy resources challenge the ways in which the existing energy system operates. Studies suggest that residential buildings can provide a flexibility service for district heating (DH) systems. This technique involves load shifting by heating buildings to higher temperatures at times when energy is more readily available, thus diminishing heating needs at times of peak demand or when energy is scarce. Based on three Future Workshops (FWs) where DH professionals and other relevant DH stakeholders participated and discussed this topic, this paper reports on the extent to which these actors see energy flexibility as a realistic future development, and on what they see as key potentials and challenges in that regard. Preliminary results indicate that the mix of the actors and the specific local context greatly influence how this topic is understood, emphasizing the importance of including local context in investigations of energy flexibility. FW participants included representatives from DH companies, municipalities, building associations, technology developers, etc. The FWs were conducted at three different localities of Denmark: Copenhagen, Aalborg and Sønderborg, i.e. the national capital, a regional capital and a smaller city, respectively.

1. Introduction

The relative instability in energy supplies and the comparative stability in energy consumption patterns, with fluctuations during the day and the year, is a key challenge as the energy systems include more renewable energy resources (RES), for example wind and solar [1–3]. Studies suggest that residential buildings may contribute to the management of such flexibility in the district heating (DH) sector as buildings can be used for short term heat storage. Realizing this potential entails increasing the temperature in buildings when renewable energy is more readily available, thus diminishing heating demands during the times of the day when energy is in peak use [4].

However, to assess the feasibility of such proactive use of residential buildings to manage instability in heating related energy consumption patterns, more in-depth understandings of the agency and behaviour of the actors using those buildings is necessary. Obtaining such knowledge entails gaining greater insights into everyday residential household practices and potential for change, i.e. insights into the patterns of heating related energy consumption among residents living in different types of



households. The question is if the technical potential for using buildings to manage flexibility in the DH system is both practically realizable *and* compatible with patterns of energy consumption in households, and in this regard if the relevant actors are willing to - or are indeed practically able to – change and adapt their heating related energy consumption. Questions of comfort, consumer sovereignty and top-down control versus individual freedom are at the fore.

1.1 The DH socio-technical system, interdisciplinary competencies and collaboration

Understanding the full potentiality of this future vision for integrating buildings actively into the energy system requires cross-sectorial and technical integration. It requires involving the multiple sector-professionals that work at all levels of the energy production and distribution system [5], and it requires assessments of the potential for change of practices in the residential buildings that will potentially be used more proactively for heat storage. In other words, understanding what is currently at stake for DH, and in this light what the potentials for change are, requires both insights and understanding of the dynamics in the complete socio-technical systems that ultimately deliver DH to the end-users.

The complexity of such analysis calls for the integration of perspectives and analysis in the complete DH socio-technical system, ranging from micro-level perspectives (e.g. end-user perspectives or specialist technical knowledge) to macro-level perspectives (societal trends and tendencies and political decision-making), and this calls for interdisciplinary collaboration and research. To facilitate the first steps of such interdisciplinary collaboration, the Future Workshops (FWs) as a method promotes discussions of future perspectives/imagined scenarios regarding certain topics [6], typically with the participation of relevant sector professionals, members of the public and other stakeholders (see section 3).

This paper presents the preliminary results of three Future Workshops where DH professionals and other relevant DH stakeholders participated and discussed the potential use of residential buildings to manage flexibility in the district heating systems. Specifically, this paper reports on the extent to which these actors see energy flexibility as a realistic future development, and on what they see as key potentials and challenges in that regard.

The paper is organized in the following way: Section 2 introduces the relevant technical perspectives of the case for using residential buildings to manage flexibility in the DH system; section 3 describes the FWs as a method; the preliminary findings/results from the FWs are presented in section 4. Finally, the implications for practice and future research are discussed in section 5.

2. Technical perspective: the potential for using residential houses to manage DH flexibility

The increasing share of renewable energy resources (RES) in the energy system can induce a mismatch between energy use and production, thus creating a challenge for the stability of energy grids. To solve this problem, increasing efforts have been made to develop smart technologies [3] that are able to manage a RES-dominated and thus more intermittent energy network [2]. Coupling this total network (including electrical, thermal and gas grids, various forms of energy storage, electric transportations, local industries and buildings) with smart metering and control networks can account for the actions of all the actors in the network. This will enable more reliable management of energy supplies, increasingly based on the more intermittent RES energy production.

In this Smart Energy Grid context, a new paradigm has emerged when considering the building stock: Buildings are no longer considered as passive energy end-users. On the contrary, as an important and potentially active element of the energy grid, buildings can not only modulate their energy use, but also store, produce, self-consume or re-inject a significant share of energy. Thus, buildings may help reduce the mismatch between instantaneous energy use and energy consumption, in this way enhancing the integration of RES in the grid. Such demand side management techniques, also known as building energy flexibility strategies, can help to solve local or global congestion issues occurring at critical periods in the weak points of the bottleneck of a grid.

Within this network, the same technique can be applied to district heating specifically. Here, the energy flexible buildings can use what is known as penalty signals¹ as control information from the DH system to modulate the heat energy demand time profile. In this way, energy use can be shifted in time. This technique is also known as load shifting. This means that energy use can be shifted from critical periods, for example when heat demand is high, heat energy production is costly or has a high CO₂ release intensity, and towards periods of time when there are more abundant supplies of RES production, CO₂ release intensity is less and the production cost is also lower (see *Figure 1*). Additionally, maximum heat power peak demand often drives the limiting sizing factors of DH production and distribution systems. High peak power demands induce oversizing of the DH production units and distribution infrastructures, which are only rarely used at full capacity. In other words, the use of building energy flexibility strategies can reduce investment and operation costs for the DH systems by performing what has also been known as peak shaving and valley filling (see *Figure 1*). There are different perspectives to take into account when considering the use of buildings for managing heating energy flexibility: the amount of heat shifted in time, the duration of this flexible window, the direction of the change (increase or decrease compared to non-flexible case), and the costs of activating this heating energy flexibility.

Currently, there is no scientific agreement on the definition and assessment of (heating) energy flexibility. However, the latter is usually defined as “*the ability for a building to adapt its profile of energy use to the requirements of the grid (penalty signal) without jeopardizing technical and comfort constraints*” [7]. Most of the current research focuses on the heating energy flexibility of single buildings. However, in the case of a large scale implementation of demand side management, heating energy flexibility should be analyzed at a larger scale, in this way considering the aggregated flexibility potential of building clusters, neighborhoods or even entire cities. This will also account for the significant time constant of the DH or cooling networks.

The building stock has potential for thermal storage in hot water tanks (heating system and/or domestic hot water tank) [8] and in the thermal mass of its structure and indoor environment [9]. The latter can be used as a cost-effective thermal storage solution when employing indoor temperature set-point modulation [10], and excess RES production can thus be stored in the built environment. This allows for significant space heating energy shifting over a few hours for poorly insulated buildings, and for more than 24 hours for well-insulated buildings with large effective thermal inertia [11]. This also allows for heat power demand reductions in peak power periods, especially in the morning.

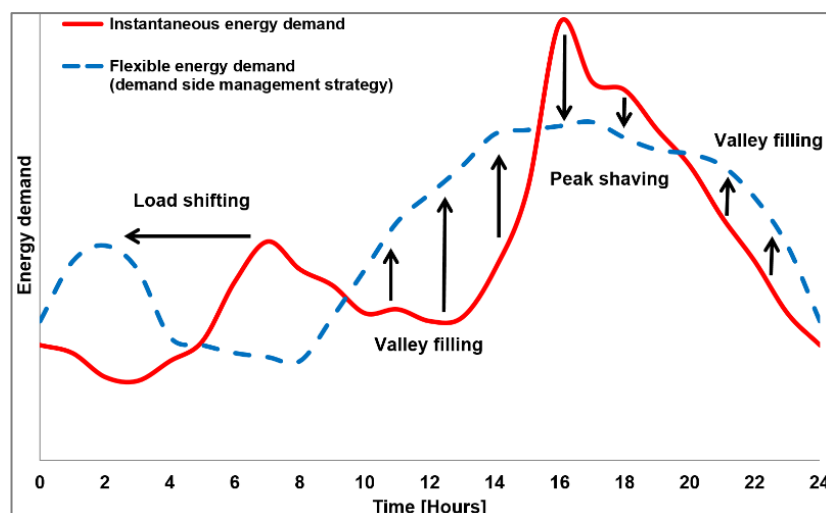


Figure 1: Example of demand side management / energy flexibility strategy with peak shaving, valley filling and load shifting.

¹ Heating energy price, CO₂ intensity of current heating energy production, local state of the DH distribution network, marginal heat production cost, etc.

3. The Future Workshops as a method

Since the potential DH transition processes require rethinking well-established structures, services and DH business models, it can be assumed that disparate parties will have to work together in novel ways for such a system to become a reality. However, in order to develop new ways of working across professional boundaries, the many different professional perspectives on such transition processes must be identified. The FW method is well suited for this.

The Future Workshop is a method developed by Robert Jungk and Norbert Müllert in 1987. The method was originally developed to support democratic, participative and collective decision making between community groups on a shared future, and for many years FWs have proven valuable as instruments for communication about planning and the creation of future visions and scenarios for certain topics. FW have been particularly prevalent within the domains of education, software design, and health [12,13].

3.1. The Future Workshops in practise

For this purpose, the future workshop method was inspired by the generic structure of the so-called ACTVOD-method [14], and thus the FWs were specifically adjusted to facilitate the inter-professional sharing of experiences and perspectives on a future intermittent energy system. More specifically, the overall aim of these FWs was to facilitate discussions between sector professionals on the potentials of and challenges for using residential buildings as flexibility generators in the district heating system, and thus the FW design also aimed for the discovery of collaborative and efficient ways to explore the potential for the integration of buildings to provide flexibility in the DH system.

Three FWs were organized at different locations in Denmark (Sønderborg, Aalborg and Copenhagen), and these covered both rural and urban areas. For each workshop, key local professionals were invited. These included representatives from municipalities, utilities, housing associations, private companies, and technology developers. The participants were divided into groups of 5-6, comprising a mix of different professionals. A total of 36 participants divided into 7 groups took part in the FWs. All three workshop were started with a short introduction and organized in three main phases: These phases included I) mapping, identification and prioritization of main actors and infrastructures relevant for the realization of an intermittent district heating system and the challenges associated with this; II) visualization of visions for solving the identified challenges; and III) critical discussions of the feasibility of these visions.



The FWs were carried out with the help of game boards with concentric circles in various colors. On these game boards, FW participants indicated their chosen prioritizations of given topics via notes/post-its (*see Figure 2*)

Figure 2: Example of Future Workshops game boards.

During the first phase (I) of the FWs, the participants were individually asked to identify different actors of relevance for realizing a transition to a more flexible district heating system. The identified actors were written down on separate cards, and then prioritized by the groups according to their importance. For this purpose, each group was asked to place and to prioritize the different actors according to their importance on the concentric circles, with the inner circle representing the highest priority and the outer circle representing the lowest priority. Participants were then asked to attach small notes for each of the actors, explaining what they saw as a central challenge for the specific actor in relation to the topic. The process was then repeated, but this time focusing on the identification and prioritization of technologies and infrastructures deemed important for achieving a more flexible DH system. Inspired by the previous exercises, in the second phase (II) the participants were asked to identify and describe what they saw as the two most important challenges for realizing the DH transformation. Based on these choices, the

groups were asked to visualize their ideal visions for a future that addressed these challenges. Finally, in the third phase (III) the participants took part in a common discussion on the feasibility of the realization of the presented visions for the future of DH. In other words, leaning on the expertise and insights of these sector professionals, the FWs created an opportunity to glimpse into future visions and scenarios for the DH systems based on the different types of sector expertise represented in the FWs. These all reflected different perspectives and analysis' of the DH system and future potential.

4. The Future Workshops: preliminary insights

In the following sections, preliminary findings/results from the FWs are presented. All of these findings are based on video-documentation from the FWs, on the collected notes and drawings from the FWs and on the summary report authored by Pernille V. K. Andersen, Anders Horsbøl and Emil Styrbæk Møller (see [15]). Here, the selected key findings from the FWs are presented in the same order as phases I, II and III of the workshops described in section 3.1.²

4.1. DH transitions: key actors and technologies as anticipated by FW participants

In groups, the FWs participants were asked to prioritize what they saw as among the most important actors for the integration of households in the future flexible DH systems. The groups could choose various actors as among the most important. 6 of the total 7 FW groups prioritized national politicians/authorities and utilities, 4 of the 7 groups prioritized housing residents, their organizations and different types of landlords, and 2 FW groups prioritized municipalities as among the most important.

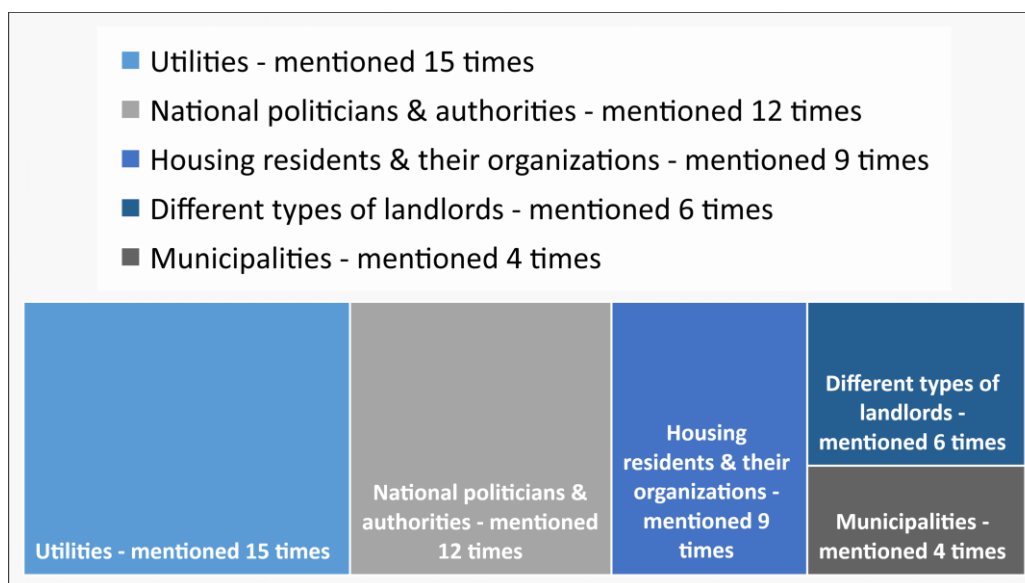


Figure 3: This graph shows the amount of times these key actors were mentioned when FW participants answered the question: What are/should be the most important actors for the integration of households in the future flexible DH systems? The size of the boxes represent the relative amount of times the actors were mentioned.

² The findings presented here are a part of a much larger dataset. This dataset will be analysed further to understand the professionals' different stakes in, attitudes towards and perspectives on the energy system more in-depth.

Evidently, there were very different perspectives on the role of residency-owners among the FW participants. This is underlined in the following quotes from the FWs:

Private company employee: *"We have this experience with the public that (...) they [the end users] just expect that there is heating in the radiator [Utility employee: Yeah, and that it's environmentally friendly how it's done] and there is water in the taps."* Social housing representative: *"Actually, I don't really agree with you there. I think that the end-users have a lot to say."* (...) Energy consultant: *"I think that they [the residents] are pretty significant. [As a resident in my] apartment I want to be able to control what heating I have. And I meet a lot of people who want to sleep in a very cold bedroom. [And] if I look at the fluctuations, I think ... well maybe it's during the night that you want to turn the heating on a bit when the wind turbines are producing, like ..."* Utility employee: *"That's when you want it cold."* Energy consultant: *"I know a lot of people who (...) want to control it themselves. (...) Where are we at if, as a consumer, you can't even control how the heating is on...?"*³

Overall, some FW participants emphasized the end-user preference of individual choice, while others argued that more top-down control would be necessary if these techniques are to work. These perspectives represent different extremes in views on individual freedom/consumer choice versus top-down controlled planning. Buildings and building design overall was mentioned as a part of the DH system transition by 5 out of the 7 groups in total. Moreover, the degree to which this was considered a viable and realizable option seemed to vary considerably from region to region. Actors judged as second-most important for the DH transitions overall were consultants, researchers, relevant tech-industries, janitors and other sector-related craftsmen.

When asked what they saw as the main and important technologies and techniques in achieving the potential transformation of the DH sector (I), 6 out of the 7 workgroups mentioned the word "control" 11 times in total, and 5 of the groups prioritized this concept as most important. To what extent the groups were thinking in terms of control/management at end-user level was not always quite clear, however. While 3 of the 7 groups mentioned several variations of the notion of data collection as an important technology for flexibility in the DH sector, this was never prioritized most. Words also mentioned, albeit less frequently, were "surveillance", "sensors" and "smart technologies." Incentives were also discussed, but these were never highly prioritized by the workshop participants.

4.2. DH transitions: key future challenges as anticipated by FW participants

Based on the reflections among FWs participants regarding key technologies and actors in the DH transition processes, groups were also asked to specify what they considered the most critical future challenges (and potentials) for integrating residential buildings more proactively into the DH system for managing flexibility (II & III).

The groups summarized the key challenges for such a potential DH transition via the following themes: A) The current political/governance framework, here particularly the challenges in creating political systems facilitating long-term strategizing and thinking in energy systems integration, data-sharing and system compatibility. B) Systems flexibility, here the need for managing daily flexibility and seasonal flexibility in supply, and in this context also the need to view the energy systems holistically, i.e. including electricity, gas, excess heating, geothermal systems etc. The importance of mentioning and *defining* the different types of flexibility was also highlighted. C) Challenges in identifying viable businesses cases and business models, here including long-term investment security comprising the potential for integrating novel systems innovations. D) Insufficient documentation of the potentials for flexibility in the DH system, too few demonstration projects and questions of data accessibility. E) Another key challenge and question concerned the management / facilitation of the DH transition process, for example, which actors or types of actors within the DH system will be in charge? F) As a future potential, pricing structures as motivation were also mentioned, here comprising thoughts

³ These quotes are from the Future Workshop in Copenhagen. The quotes are translated from Danish to English by the authors.

on, for example, enhancing a better understanding of pricing structures among the end-users, rewarding end-users for doing ‘the right thing’ (incentives) and seeking to influence consumption choices.

4.3. DH transitions: on intra-sectorial differences and perceptions of these among FW participants

While the technical potential for actively integrating buildings into the energy system (and particularly the DH system) is there (see section 2), multiple uncertainties prevail: Not only is the collaboration of actors that use buildings a prerequisite for the success of this technique, as the quotes below underscore, there are also multiple structural differences and challenges within the sector itself:

Private company employee 2: *“Well ... I certainly know district heating companies that complain that their production price is expensive in these times of peak demand. (...) But I think it is very different from district heating plant to district heating plant what sort of challenges they have with this sort of stuff.”* (...) Private company employee 1: *“and there isn’t really any ... if the users are ready to receive, I mean, if the houses are designed so that they are ready to receive these kinds of flexible solutions ...”*

⁴

Evidently, some actors from utilities and district heating plants saw the potential of using buildings more proactively in the management of the DH system, and in different ways, some utilities and companies are already experimenting with some of these techniques. Other actors and utilities see less (or no) potential in this regard. Preliminary research evidence suggests that the diverse nature of the utilities may inform future outlooks for DH among the sector professionals: For example, the size and technical infrastructure of utilities themselves may hold different (immediate) potentials for the use of buildings for flexibility management. This may inform the future visions and imagined prospective potentials for, in this case, the DH sector of the actors involved in those places [16]. Overall, via the FWs it is difficult to precisely trace the extent to which different sector professionals are thinking in terms of integrating buildings in the DH sector more proactively, in what way they may be doing so, and what the nature of the differences in these future outlooks among different sector professionals may practically imply.

5. The Future Workshops: implications for practice, policy and research

5.1 Methodological reflections

In this research, the FWs were developed to facilitate inter-professional sharing of experiences and perspectives, including discussions on the potentials, challenges and visions for a future intermittent energy system.

What these particular FWs also underlined is the importance of who participates; i.e. what background do the participants have, and in what way are they associated with the FW topic. People who are less knowledgeable of, for example, the DH infrastructure, practice and relevant governance framework may see and imagine novel and creative systems solutions, while people who work within the sector may be more pragmatic in their approach. Potentially, this synergy may be both constructive and innovative (as was the original intention of the FWs). Importantly, FW group dynamics, for example power-plays among the FW participants, will inform the nature of the conversation as the workshop proceeds. A less fortunate consequence of inviting very heterogeneous participants could be that the conversation is difficult because people are just too ‘far apart’ in their approaches to and perspectives on the questions. While different types of insights are hopefully produced via FWs that include a broad panel of relevant stakeholders, overall critically ‘thinking through’ the potential impact of different ‘levels’ of systems expertise and/or systems insights for dialogue among the FWs participants is crucial.

5.2 Implications for practice and research

The FWs were held at three different locations in Denmark. Interestingly, the FWs held at these different Danish locations, and thus with invited DH stakeholders and sector professionals that mostly referred to the local DH plants, had quite different outcomes. This emphasizes the importance of regional variations in the DH sector in several ways: a) The technical infrastructure of specific DH plants matter for the

⁴ These quotes from the Future Workshop in Aalborg.

challenges that the different sector professionals face and the way they think, here in terms of integrating buildings in the DH sector more proactively. Accordingly, b) local contexts matter for what future visions and perspectives are imagined among FW participants, just as differences among sector professionals themselves matter.

Considering the diversity among DH plants in Denmark alone [17], the degree of variation which is considered viable and realizable, here regarding residential building energy flexibility in DH systems, is hardly surprising. Practically, however, this also suggests that the potential integration of this strategy for DH flexibility management may have very local variations.

While the technical potential for integrating residential households more pro-actively in the DH systems for managing flexibility is there [4], the extent to which this is imagined as possible depends on the nature of the local DH socio-technical systems. Crucially, it also depends on the household residents, and on the extent to which they are willing to - and indeed able to – adapt their heating related energy consumption patterns to meet the needs for this potential transition.

Perhaps the observed diversity in the FWs among the multiple energy system stakeholders, with different stakes in, attitudes towards and perspectives on the energy system (and on energy transformations overall), should be expected. Accordingly, perhaps some level of friction, deriving from value differences and priorities amongst the diverse actors and stakeholders throughout the entire DH socio-technical system, should also be expected. Overall, more research is needed to understand and trace the dynamic interaction of these divergent views on and assessments of future potentials and challenges for the DH system among the stakeholders involved, and accordingly what this implies for energy transitions related practice and policy.

6. Conclusion

As a result of societal transitions to renewable energy resources, sometimes there are mismatches between the levels of energy production and energy consumption. In the case of district heating, research suggests that buildings/residential houses may be used proactively to manage DH related flexibility in energy use and consumption.

In this research, FWs, with various DH sector stakeholders, were designed to focus on visions and predictions for the potentials and challenges of more proactively integrating residential houses in the DH sector to manage energy flexibility. According to the FW participants, some of the challenges for achieving this DH systems transition revolved around: the political/governance framework, including current policy challenges of doing long-term investments, lack of demonstration projects, challenges of data accessibility, and the overarching question of who manages such transitions. The FWs also revealed significant regional differences in views and perspectives on this possible DH systems change.

While the technical potential for using residential buildings to manage DH systems flexibility is there, certain questions linger. For example: is this compatible with household energy consumption patterns? Are household residents able to – or willing to – change/adapt their energy consumption patterns? To fully understand the divergent views on the potential for DH systems transitions among the diverse sector stakeholders, the importance of the DH local systems context, and what this all implies for DH related future practice and policy, more research would be beneficial. To this end, the FWs as a method may prove useful for future research enquiry.

Acknowledgements

This work was financed by the InterHUB project, funded by Aalborg University' strategic funding for interdisciplinary research. InterHUB: Intermittent energy – Integrating Households, Utilities and Buildings. For more information on the project see: www.interhub.aau.dk

References

- [1] IEA. International Energy Agency 2017 *Energy Policies of IEA Countries - Denmark 2017 Review*

- [2] Mathiesen B V., Lund H, Connolly D, Wenzel H, Østergaard P A, Möller B, Nielsen S, Ridjan I, Karnøe P, Sperling K and Hvelplund F K 2015 Smart Energy Systems for coherent 100% renewable energy and transport solutions *Appl. Energy* **145** 139–54
- [3] European Commission 2006 *European SmartGrids Technology Platform Vision and strategy for Europe's Electricity Networks of the Future* vol 19 (Brussels)
- [4] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen J E, Hvelplund F and Mathiesen B V 2014 4th Generation District Heating (4GDH) *Energy* **68** 1–11
- [5] Lund H, Østergaard P A, Connolly D and Mathiesen B V 2017 Smart energy and smart energy systems *Energy* **137** 556–65
- [6] Jungk R and Müllert N 1987 *Future workshops: How to create desirable futures* (London: Institute for Social Inventions)
- [7] Reynders G, Amaral Lopes R, Marszał-Pomianowska A, Aelenei D, Martins J and Saelens D 2018 Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage *Energy Build.* **166** 372–90
- [8] Arteconi A, Hewitt N J and Polonara F 2013 Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems *Appl. Therm. Eng.* **51** 155–65
- [9] Johra H and Heiselberg P 2017 Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review *Renew. Sustain. Energy Rev.* **69** 19–32
- [10] Hedegaard K, Mathiesen B V, Lund H and Heiselberg P 2012 Wind power integration using individual heat pumps - Analysis of different heat storage options *Energy* **47** 284–93
- [11] Dréau H J P H J Le 2019 Influence of envelope; structural thermal mass and indoor content on the building heating energy flexibility *Energy Build.* **183** 325–39
- [12] M. G J . K 1991 *Design at Work - Cooperative Design of Computer Systems* ed J Greenbaum and M Kyng (New Jersey, USA: Lawrence Erlbaum Associates Publishers)
- [13] Müller M and Druin J 2012 Participatory Design. The Third space *The Human - Computer Interaction Handbook* ed J A Jacko (CRC Press)
- [14] Lauttamäki V 2016 ACTVOD-futures workshop – a generic structure for a one-day futures workshop *Foresight* **18** 156–71
- [15] Andersen P V K, Horsbøl A and Møller E S 2019 *Interhub Future Workshops: sammenfatning af indsigter* (Allborg)
- [16] Upham P, Bögel P M and Johansen K 2019 *Energy Transitions and Social Psychology: A Sociotechnical Perspective* (Abingdon & New York: Routledge)
- [17] Danish Energy Agency 2017 *Regulation and planning of district heating in Denmark*