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District Heating Systems: An Analysis of Strengths, Weaknesses, Opportunities, and Threats of the 4GDH

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Abstract: Fourth-generation district heating networks (4GDH) can play a special role in the efficient and climate-friendly use of energy. In this study, we have examined the strengths, weaknesses, opportunities, and threats (SWOT) of this innovative technology. Using a combination of qualitative and quantitative research methods, we assessed the SWOT-factors in terms of their importance. Among the factors that were weighted with the highest relative importance were the ability of 4GDH to serve as a label bundling and stimulating considerations with respect to the further development of district heating systems and the increased value creation within the national economy through the inclusion of local, renewable energy sources. Moreover, the interviewed experts agreed that regulatory frameworks in the context of 4GDH have to be further developed.

Keywords: district heating; 4GDH; SWOT

1. Introduction

Climate change has severe consequences for nature and humanity, including sea level rise, ocean acidification, and ecosystems loss [1]. The energy transition towards renewables is crucial for reducing greenhouse gases and, thus, for mitigating climate change. The heating and cooling sector is the largest single source of energy demand in Europe [2]. In the European Union, approximately 50% (6350 TWh) of the final energy demand in 2015 was used for heating and cooling. Since more than 65% of the consumed energy was produced by fossil fuels [3], this sector has a significant potential to reduce greenhouse gas emissions. To reduce greenhouse gas emission from the heating and cooling sector, (i) energy usage must be reduced, (ii) systems have to integrate more renewable and excess energy, (ii) the efficiency for generating, distributing, and using energy has to be improved. The concept of smart energy systems was introduced by Lund et al. [4] to explore synergies between different sectors. District heating has the potential to play a key role in future smart energy systems [5,6]. Historically, the development of district heating has been classified into different generations. The first generation of district heating systems was first installed in the United States of America in the 1880s; these systems were based on steam, which led to high heat losses and dangerous operational conditions. Systems of the first generation are still used today (e.g., in Paris or New York). Starting in 1930, the first district heating systems based on pressurized hot water were built. These systems belong to the second generation of district heating. The supply temperature in most systems was above 100 °C. In the 1970s, the third generation of district heating systems was introduced. The main difference to the previous generation was a lower supply temperature. Additionally, the first renewables were integrated into the system. The fourth generation concept (4th generation district heating (4GDH)) aims to achieve an integral role for district heating systems in an overall intelligent energy system. The main differences to the previous generation are lower supply temperatures, the integration of low-temperature excess heat, and the integration of large shares of renewable heat sources [6,7]. The introduction of 4GDH involves technical challenges, such has low supply temperatures [8,9], large-scale renewable energy integration [10,11], or the integration of storage technologies [12,13], but also non-technical challenges, such as consumer acceptance [14,15], new business models for district heating [16,17], or regulatory frameworks [18,19]. Figure 1 shows a keyword analysis on Scopus [20].

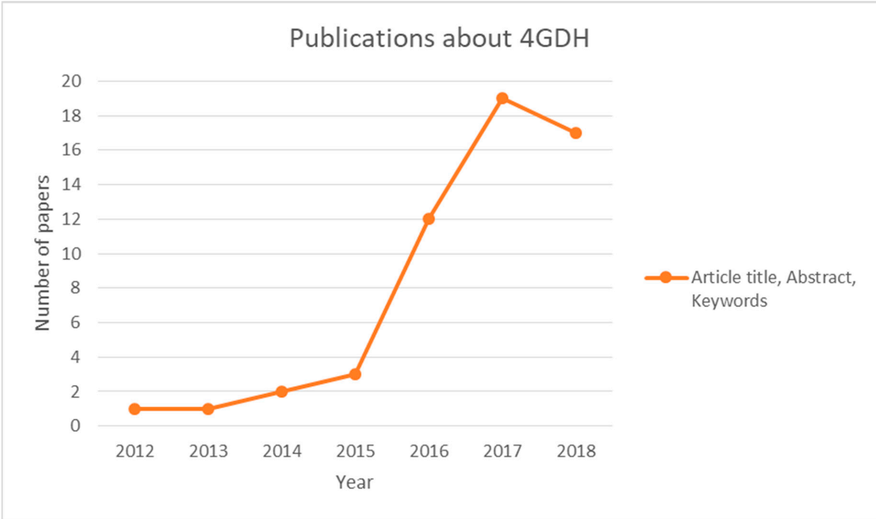

Figure 1. The number of publications between 2012 and 2018 that include the term 4th generation district heating in their article title, abstract, or keywords according to the literature database *Scopus*. A significant increase in such publications can be observed between 2015 and 2017.

Since it is a relatively new concept, an elaborate analysis of its technology-inherent strengths and weaknesses and external opportunities and threats of the technology environment is lacking. This study thus aims to identify the most important strengths, weaknesses, opportunities, and threats (SWOT)—the factors that might significantly influence the further development and dissemination of 4GDH, both positively and negatively.

Main Contribution

The major contribution of this research is a comprehensive discussion about 4GDH based on a survey of expert opinion. Therefore, we carried out a two-stage empirical study with the participation of 41 experts in the field of district heating with an involvement in the 4GDH system. We applied a hybrid method by combining a SWOT analysis with an analytic hierarchy process (AHP), resulting in a SWOT-AHP analysis. To the authors' knowledge, a research design of this kind is novel in the field. Furthermore, we asked experts about research gaps in the field of 4GDH. The questionnaire, together with all quantitative answers, is freely available at GitHub: https://github.com/GersHub/Survey-on-4GDH.

2. Method

To achieve this goal, we pursued a three-stage research plan, consisting of a literature review, qualitative expert interviews, and a quantitative expert survey. First, we analyzed the relevant scientific literature to identify those aspects and challenges that scholars considered to be particularly important for the further development of the technology. Based on this, we employed a two-stage empirical survey. The purpose of the first empirical round was to validate or extend the factors that had been derived from the literature by expert interviews. For the development and dissemination of 4GDH, we identified four major expert groups: (i) academia, (ii) energy providers/network operations, (iii) public authorities, and (iv) building project organizers. We selected the individual experts from academia based on their number of publications on 4GDH or related topics that are listed in the literature database *Scopus* [20]. The experts from practice were chosen according to their actual or potential involvement in 4GDH projects. In the first empirical round, we invited a total of ten persons to qualitative interviews, of which eight agreed (see Table 1).

Table 1. Composition of the samples of the first and second phases of the empirical survey.

Approach	Research	Practitioner				
	Academic Experts	Public Authorities	Building Project Organizers	Network Operators	Other	Total
SWOT Phase 1 qualitative	3	2	2	1	-	8
SWOT Phase 2 semi-quantitative	24	4	3	8	2	41
Qualitative Questions (Phase 2)	24	3	3	8	2	40

In these interviews, which took place in April 2019, we introduced the topics in a very broad context and asked open questions to avoid possible biased answers and to avoid missing important issues and perspectives. We transcribed the interviews and conducted a qualitative content analysis of the answers, following the method by Mayring [21] for systematic text analysis. The analysis ended in a list of relevant technology-inherent strengths and weaknesses, as well as technology-external opportunities and threats of 4GDH, representing the findings from the literature review and the first round of expert interviews.

Subsequently, we carried out a second round of expert survey, to get expert judgments on the relative importance of the SWOT-factors. For this, we applied the analytic hierarchy process (AHP) method, according to Saaty [22]. The AHP method has been applied in a wide range of different studies, such as on strategic energy management in industry [23], renewable energy technologies [24,25], or modeling and simulation techniques [26,27]. The goal of the combination of a SWOT and an AHP analysis is to quantify the relative importance of the respective SWOT factors. In our second empirical round, 148 experts from the four expert groups received the link to an online survey constructed with the survey tool Lime Survey, leading to a total number of 41 complete answers; 24 of them from academics and 17 from practitioners (see Table 1). Thus, the response rate was 27.7%.

In the online survey, experts were asked to compare each factor in a SWOT group with all other factors in the respective group in pairs, for example, to determine which strength is more important for each pair of strengths and how much more important. The relative importance of the factors could be classified using a nine-level ratio scale proposed by Saaty [28]. The scale ranged from 9:1 (the first factor is considered to be much more important than the second factor) to 1:9 (the second factor is considered to be much more important than the first factor). The middle of the scale was 1:1 and meant that both factors were considered equally important. Even numbers were omitted as intermediate values to not offer a too high number of gradations that would have exceeded the human ability to differentiate. Since we had three factors in each SWOT group, three comparisons were necessary within each group following the logic explained above. Hereby, we randomly changed the order in which the SWOT factors were compared so that the order could not lead to a systematic bias of the answers. After the pair comparisons in each SWOT category, the experts were also asked to name other potentially important factors that had not been considered in the pair comparisons. After the comparisons within the four SWOT categories, the experts had to make comparisons between the four SWOT groups, which required an additional six comparisons.

The results of the pair comparisons show the relative importance of one factor relative to the other. Thus, the importance of factor a relative to factor b given by expert i can be represented by the quotient $w(a)_i/w(b)_i$. If the quotient results in an odd number from 3 to 9, this means that factor a is considered more important than factor b; the reciprocal value means that factor b is considered more important than factor *a*; the value 1 means that both factors are equally important. We have aggregated the results of the comparisons by individual experts by calculating the average values of all respondents within the respective groups. Then, we have normalized these values so that the less important factor gets always the value 1, and consequently, the more important factor a value between 1 and 9.

These normalized values and their reciprocal values were subsequently entered into the five evaluation matrices, one 3×3 matrix for each SWOT category and one 4×4 matrix for comparing the SWOT categories with each other. We used the eigenvalue method, according to Saaty [22] to calculate the weighting factors and relative priorities. Here, we squared the judgment matrices, calculated the sums for each line, and normalized the values so that the vector sums to 1. We repeated this process until the difference between the values in the vector became marginal. In this case, the highest difference between the values of the first and the second vector was already as low as 0.002, so that only one repetition was necessary. Further, we calculated the consistency ratios for each judgment matrix, according to Saaty [22]. Finally, we multiplied the values of the eigenvectors of the judgment matrices for each SWOT category (local priorities) with the weighting factor of the respective SWOT group. In this way, we obtained the overall weighting factors for all the SWOT factors, again normalized so that they sum to 1.

In addition to the pair-wise comparisons, we added qualitative questions in the survey to gain further information about research fields in the context of 4GDH. We asked the experts to assess their level of agreement with 13 statements on a seven-level Likert scale. The possible levels at the scale were *(7) Entirely agree*, *(6) Mostly agree*, *(5) Somewhat agree*, *(4) Neither agree nor disagree*, *(3) Somewhat disagree*, *(2) Mostly disagree* and *(1) Entirely disagree*. In total, 40 respondents completed this part of the survey (see Table 1).

2.1. Presentation of the Results

Hallowell and Gambatese [29] pointed out that the median value is preferable to the mean value for presenting and discussing results; the median value is less prone to outliers. Sachs [30] argued that the interpolated median is better suited than the median value. The interpolated median gives a measure within the lower and upper bound of the median, in the direction that makes the data more heavily weighted. The interpolated median is calculated as follows:

$$IM = \begin{cases} M \; if \; n_2 = 0 \\ M - 0.5 + \frac{0.5N - n_1}{n_2} \; if \; n_2 \neq 0 \end{cases}, \quad (1)$$

where N stands for the total number of responses, n_1 for the number of values strictly lower than M, and n_2 for the number of values equal to M [31]. The responses are analyzed in terms of their interpolated median (IM), median (M), and mean. This should guarantee a transparent presentation of the results. Furthermore, the results of the quantitative questions are presented in a bar chart in the Appendix A.

2.2. Threats to Validity and Limitations of the Study

There is no general criterion that allows an unbiased comparison of the impact of a researcher's work. This applies, in particular, to the comparison between disciplines. The selection of scientific experts for this study was based entirely on the number of publications. The authors are aware that this is a threat to validity. However, the authors claim that this is the most transparent selection procedure. Experts from industry were selected based on their actual or potential involvement in 4GDH projects. This selection process ensured that experts from industry who do not publish their work in peer-reviewed journals, nevertheless, participated in the survey. The experts who participated in this study had to have experience in the field of 4GDH systems. This could be considered as unrepresentative as the assessment of experts in the field of district heating, who have no experience in the field of 4GDH systems, could be considered very valuable. The same applies, however, to experts whose expertise is even broader, e.g., in the field of smart cities (energy, transport, ICT, etc.). This paper thus presents an assessment of SWOT factors by experts who are familiar with the technology. Experts who have experience with 4GDH systems may be biased because they may have developed a positive attitude towards the technology.

3. Results and Discussion

This chapter presents the results and discussion of the SWOT/AHP analysis; the most significant strengths, weaknesses, opportunities, and risks of 4GDH were identified and compared according to their relative importance (Section 3.1). Furthermore, research needs in the field of 4GDH are discussed in Section 3.2.

3.1. SWOT-AHP Analysis

An overview of the SWOT factors identified in the first round can be found in Table 2.

Table 2. Summary of strengths, weaknesses, opportunities, and threats (SWOT) factors with respect to fourth-generation district heating networks (4GDH) based on the first round of interviews.

	Positive	**Negative**
Internal	**Strengths**	**Weaknesses**
	S_a: Sector coupling [32,33]	W_a: No direct supply of DHW [6,34]
	S_b: Label promoting future developments in district heating	W_b: Lacks cost efficiency in the short and middle term [7,35]
	S_c: Contribution to the decarbonization of the heating sector [36]	W_c: Difficult adaption of existing district heating networks in dense areas [37]
External	**Opportunities**	**Threats**
	O_a: Value creation within the national economy [38–42]	T_a: Decreasing heat demand [43,44]
	O_b: Tendency to low-temperature heating systems in new buildings [6,45]	T_b: Competitive technologies becoming more attractive [39,46–48]
	O_c: District heating plays an important role in the heating and cooling strategy of the European Commission [49]	T_c: Existing heat supply contracts

In the following, we describe the SWOT factors that were identified in the first round. A detailed discussion of the respective factors is beyond the scope of this paper, and we refer to the literature in Table 1.

A key feature of 4GDH systems is the connection to different sectors, such as electricity or transport (S_a). Several experts mentioned that the concept of 4GDH serves as a label that bundles and stimulates future developments in district heating (S_b); this factor is not discussed in the literature. Another feature of 4GDH, which was mentioned various times in the qualitative expert interviews, is the utilization of high shares of renewable energy sources contributing to the decarbonization of the heating sector.

Many European countries have existing regulations that require a minimum temperature of 60 °C in central hot water tanks and connected pipes to avoid the growth of Legionella bacteria in district heating networks (DHW). 4GDH systems are envisioned to be operated with lower temperatures. Therefore, a direct supply of DHW without additional heating or other water disinfection methods is not possible (W_a). Other weaknesses frequently mentioned in the first round was the cost efficiency of 4GDH, especially in the short and middle term (W_b) and difficulties in the adaption of district heating systems in dense areas (W_c). The high replacement cost of district heating networks is one reason why the New York district heating system is still operated with steam [37].

The concept of 4GDH involves a shift from fossil energy sources to renewable energy sources, which are usually sourced locally and, therefore, lead to value creation within the particular country (O_a). Especially, new buildings are equipped with panel heating (i.e., floor, ceiling, or wall heating) and have a lower heat demand because of better heat insulation compared to older buildings. Consequently, 4GDH systems are well-suited for a large number of new buildings (O_b). The European Commission mentions the expansion of highly efficient district heating and cooling networks in its Energy 2020 energy strategy (O_c) and experts see this as an opportunity.

A significant reduction in heat demand or heat demand densities evokes challenges such as higher relative heat losses. Therefore, the spread of passive houses or active houses that have low demand is a possible threat for 4GDH systems (T_a). Another potential threat mentioned by experts is alternative low-temperature heating options that are becoming more attractive; heat pumps have been mentioned several times in this context. (T_b). Various experts mentioned existing heat supply contracts as a threat; in such contracts, the consumer is guaranteed a specific supply temperature. Therefore, the consumer needs to be involved in the process of lowering the temperature in the system.

As outlined in Section 2, in the second round of interviews, an AHP was carried out to evaluate the relative importance of the SWOT-factors. Since the share of respondents who completed the entire questionnaire comprises almost equal parts by experts with an academic background and experts with a practical one, the answers of these two groups were analyzed separately. For each SWOT group, the consistency ratio (CR) was calculated and compared with the suggested limits by Saaty [28]. In two SWOT groups, the CR was too high. The CR for the comparisons in the field *Strengths* of academic experts was 14.2%, and the CR for the *Opportunities* of the practitioners was 5.1%, both higher than the suggested limit of 5%. The CR for each respondent was thus calculated, and comparisons with a significantly higher CR than the others were removed for the respective SWOT group. Four comparisons of academic experts and five comparisons of practitioners were removed. After this step, all CR were below the limit of 5% (see Tables 3 and 4). The results of the SWOT-AHP analysis are presented in Table 3 for academic experts, in Table 4 for practical experts, and in Table 5 in an aggregated way, combining academic and practical experts. Three types of relative priorities are specified in the tables: the priority of each SWOT group, the local priority of each factor within the group, and finally, the global priority of each factor. The factors with the highest priorities are marked with the superscripts *a* (purple: highest local priority) and *b* (red: highest global priority).

Table 3. Results of the SWOT/analytic hierarchy process (AHP) for academic experts.

	SWOT Factors	Local Priority	Global Priority
Strengths Priority: 0.33 CR: 1.5%	S_a: Sector coupling	0.16	0.053
	S_b: Label promoting future developments in district heating	**0.62** [a]	**0.201** [b]
	S_c: Contribution to the decarbonization of the heating sector	0.22	0.072
Weaknesses Priority: 0.13 CR: 0.6%	W_a: No direct supply of DHW	0.27	0.034
	W_b: Lacks cost efficiency in the short and middle term	**0.49** [a]	0.062
	W_c: Difficult adaption of existing district heating networks in dense areas	0.24	0.031
Opportunities Priority: 0.37 CR: 0.1%	O_a: Value creation within the national economy	**0.45** [a]	0.165
	O_b: Tendency to low-temperature heating systems in new buildings	0.24	0.087
	O_c: District heating plays an important role in the heating and cooling strategy of the European Commission	0.32	0.116
Threats Priority: 0.18 CR: 4%	T_a: Decreasing heat demand	0.36	0.070
	T_b: Competitive technologies becoming more attractive	0.27	0.037
	T_c: Existing heat supply contracts	**0.37** [a]	0.073

[a] Factor with the highest local priority in each SWOT group; [b] Factor with the highest global priority.

Table 4. Results of the SWOT/AHP for practitioners.

	SWOT Factors	Local Priority	Global Priority
Strengths Priority: 0.32 CR: 1.52%	S_a: Sector coupling S_b: Label promoting future developments in district heating S_c: Contribution to the decarbonization of the heating sector	0.15 **0.65** [a] 0.20	0.047 0.211 0.064
Weaknesses Priority: 0.14 CR: 0.2%	W_a: No direct supply of DHW W_b: Lacks cost efficiency in the short and middle term W_c: Difficult adaption of existing district heating networks in dense areas	0.30 **0.36** [a] 0.34	0.042 0.051 0.048
Opportunities Priority: 0.33 CR: 3.2%	O_a: Value creation within the national economy O_b: Tendency to low-temperature heating systems in new buildings O_c: District heating plays an important role in the heating and cooling strategy of the European Commission	**0.70** [a] 0.11 0.19	**0.231** [b] 0.037 0.063
Threats Priority: 0.20 CR: 4.6%	T_a: Decreasing heat demand T_b: Competitive technologies becoming more attractive T_c: Existing heat supply contracts	**0.44** [a] 0.26 0.30	0.079 0.066 0.059

[a] Factor with the highest local priority in each SWOT group; [b] Factor with the highest global priority.

Table 5. Results of the SWOT/AHP Analysis (aggregated way).

	SWOT Factors	Global Priority	Global Rank
Strengths Priority: 0.32 CR: 1.5%	S_a: Sector coupling S_b: Label promoting future developments in district heating S_c: Contribution to the decarbonization of the heating sector	0.05 0.205 0.068	9 **1** 5
Weaknesses Priority: 0.13 CR: 0.4%	W_a: No direct supply of DHW W_b: Lack of cost efficiency in the short and middle term W_c: Difficult adaption of existing district heating networks in dense areas	0.038 0.058 0.037	11 8 12
Opportunities Priority: 0.36 CR: 0.8%	O_a: Value creation within the national economy O_b: Tendency to low-temperature heating systems in new buildings O_c: District heating plays an important role in the heating and cooling strategy of the European Commission	0.190 0.068 0.098	2 6 3
Threats Priority: 0.19 CR: 4.3%	T_a: Decreasing heat demand T_b: Competitive technologies becoming more attractive T_c: Existing heat supply contracts	0.098 0.047 0.067	4 10 7

Please note that for the sake of clarity, the individual factors are presented in an abbreviated form. The exact wordings as they were formulated in the questionnaire can be found in Appendix B.

The number of additional SWOT factors suggested by experts was low compared to the number of respondents, and each factor was only mentioned once; thus, it can be concluded that the identified SWOT factors in the first stage of the SWOT/AHP analysis were correct. We want to stress that all factors listed in Table 2 were considered to be important by the experts. The AHP analysis ranks the individual factors. However, it does not mean that factors that are ranked low are not considered important.

Figures 2 and 3 illustrate the results graphically. Each graph is divided into four sections, one for each SWOT field, following the conventional logic strengths—weaknesses—opportunities—threats. The individual factors are named and indicated by a transparent circle. With a higher distance from the origin (0; 0), the importance of the individual factor increases. The different SWOT fields are illustrated with red or blue circles and a line marking their distance from the origin. The longer the line (i.e., the higher the distance from the origin), the greater the importance of the respective SWOT field.

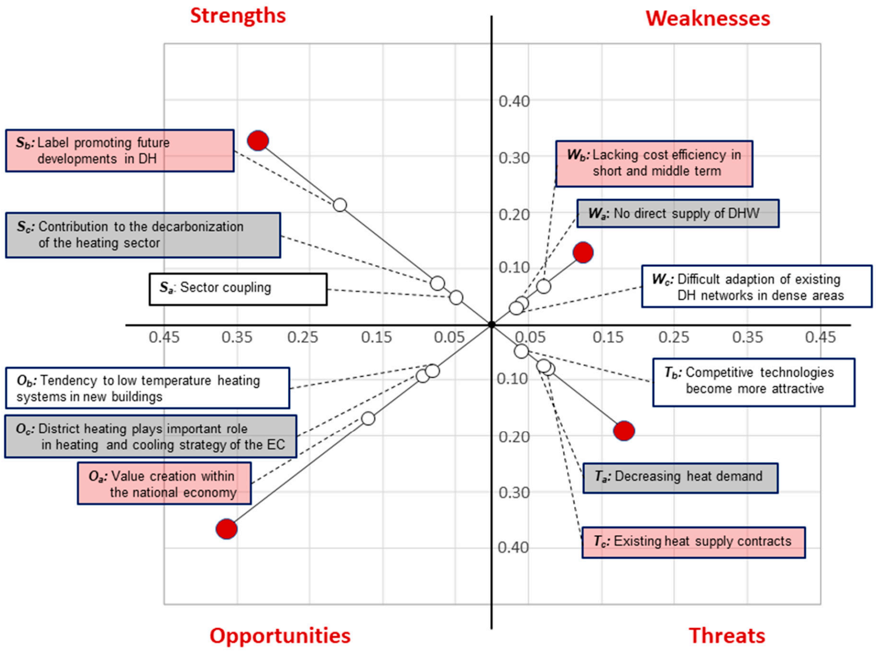

Figure 2. Results of the assessment of academic experts. The fields highlighted in red have the highest importance in the respective field; the fields highlighted in grey, the second-highest importance, and the fields highlighted in white the third-highest importance.

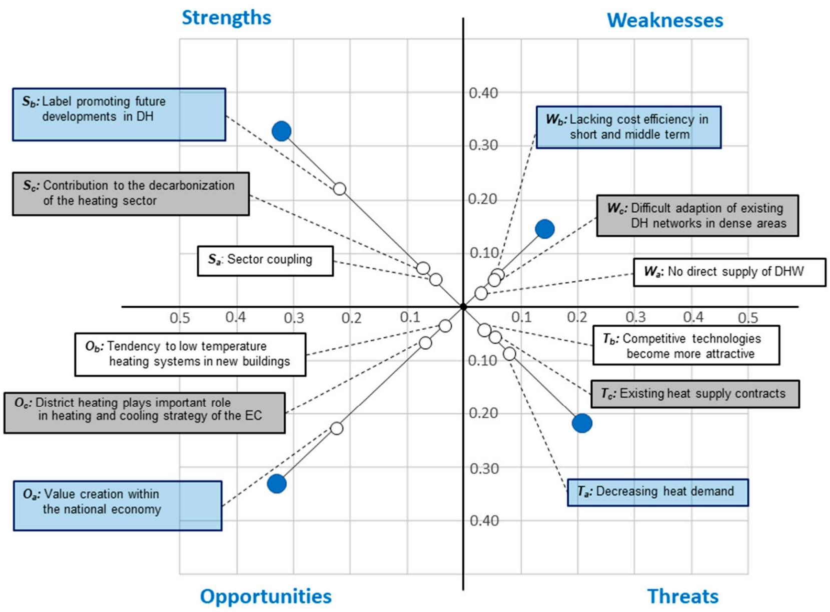

Figure 3. Results of the assessment of practitioners. The fields highlighted in blue have the highest importance in the respective field; the fields highlighted in grey, the second-highest importance, and the fields highlighted in white the third-highest importance.

The results of the academic and practitioner SWOT-AHP analysis indicate that positive factors related to strengths and opportunities dominate the negative factors, weaknesses and threats. All global priorities of positive factors are greater than or equal to 0.32; the highest global factor of negative factors is 0.2 (threats in the practitioners SWOT-AHP). Thus, it can be concluded that the participants in the expert survey attribute the concept of 4GDH a high potential. Comparing the external versus internal factors, both expert groups rated the external factors higher than their internal counterparts. This indicates that the technology environment has the potential to substantially influence the further development of 4GDH in a negative or positive way.

As can be seen in Tables 2 and 3, both expert groups assigned the greatest global importance to the same two elements. While academic experts consider the factor "*Label promoting future developments in district heating*" to be the most important of all 12 factors, practitioners considered "*Value creation within the national economy*" as most important. These two factors have a significantly higher global priority than the other factors in both expert groups. The most important global factor, according to the aggregated results (Table 4), is "*Label promoting future developments in district heating*"; it should be stressed that this factor is not discussed in the literature. Another important aspect is that the literature has already introduced 5th generation district heating systems [50,51]. The 5th generation is characterized by distribution temperatures close to that of the ground, thus allowing this to be put to work for heating and cooling systems. There is no definition as to when a new generation (in this case the 5th) is to be introduced and what can be regarded as a technical or conceptual further development of an existing generation (in this case the 4th). The authors consider the introduction of a 5th generation to be inappropriate for the following reasons: (i) the 4GDH was introduced 2014 [6] (This can be considered as the main publications, but we want to mention that the 4GDH was already mentioned in the literature in 2012.) and has bundled research and development work in the field of district heating since that time. It has established itself as a *label,* and it is doubtful whether upgrading to a new generation is beneficial to bundle research activities or in the communication to political decision-makers, industry, and the public. (ii) A *Scopus* keyword search indicates that the concept of the 5th generation is not yet widely adopted by the scientific community; only two publications have "5th generation district heating" in the article title, abstract, or keywords. (iii) The proposed enhancements compared to the 4GDH can be seen as an extension of 4GDH and do not require the introduction of a new generation. In general, we would like to point out that the successful introduction of a new generation naturally goes hand in hand with academic recognition ([6] has already more than 550 citations, according to Web of Science.). We would like to point out that experts with 4GDH experience may be biased on this question.

The factor with the second-highest priority, according to academic experts, and with the highest priority, according to practitioners, is *"Value creation within the national economy"*. Although this factor has been discussed in the literature in different contexts, a detailed analysis in several countries has not yet been published. Park et al. [40] presented a study on how consumers benefit from district heating service in Korea. National benefits were assessed on the assumption that consumers switch from individual heating to district heating.

Valodka et al. [41] analyzed the impact of renewable energy on the economy of Lithuania. They concluded that switching to biofuels in district heating would reduce the cost to the consumer by one third.

The global priority assigned to the remaining 10 factors is very close for both expert groups. They are between 0.031 and 0.116 for the academic experts and between 0.037 and 0.079 for the practical experts. Academic experts attributed the third-highest priority to the external opportunity of district heating and smart grids being included in the heating and cooling strategy of the European Commission; by contrast, those experts with a practical background rated the threat of a decreasing heat demand as the factor with the third highest priority. The strength factors "*Sector coupling*" and "*Contribution to the decarbonization of the heating sector*" were given a low global and local priority by both expert groups, even though these internal strengths are described as a core feature of 4GDH in the literature [4,6,33]. The economic performance of district heating systems compared to concurrent technologies has been widely discussed in the literature [39,46–48]. The experts consider the "*Cost efficiency in the short and middle term*" as a weakness of 4GDH. Previous research has shown that the competitiveness of district heating is particularly sensitive to heat density [7,35]. The experts consider the factor "*decreasing heat demand*" as a threat. While some authors (e.g., [46]) take lower heat demands in the future into consideration and present this factor as a precondition for 4GDH, the experts taking part in the present survey mentioned an increasing number of active or passive houses as a threat to district heating; a low heat demand could lead to district heating becoming obsolete. The threat of "*Competitive technologies*", such as heat pumps, was mentioned both in literature and in the interviews.

3.2. Additional Quantitative Questions

Following the paired comparisons of the SWOT factors, the respondents were asked the question: "To what extent do you agree to the following statements?" As already mentioned above, the possible answers ranged from (7) *Entirely agree* to *(1) Entirely disagree* on a seven-point Likert scale. The subsequent Tables 6 and 7 show the mean, median, and interpolated median of the answers for the respective questions separated in the answers of academic experts and practitioners. All results are displayed in a bar chart in the Appendix A.

Table 6. Statistical analysis of the answers of academic experts.

	Mean	Median	Interp. Median
Regulatory frameworks for 4GDH are already developed (e.g., bans on oil and gas boilers, CO_2 taxes...).	2.88	2	2.23
User confidence in new technology has been sufficiently investigated.	2.83	2.5	2.50
Facilitating active consumer participation has been sufficiently investigated (e.g., via mobile applications, gamification).	3.29	3	3.13
User behavior has been sufficiently investigated (e.g., increasing comfort standard).	3.46	3	3.17
Sophisticated control tools have already been developed and available (cross-domain, fully dynamic analysis; predictive control algorithms).	3.50	3.5	3.50
The impact of temperature errors in district heating systems has been sufficiently investigated (e.g., substations generating too high return temperatures).	3.46	3.5	3.50
Construction standards have been consequently considered to avoid peak demands (e.g., by integrating storage mass into buildings).	3.50	4	3.67
Smart metering (with intelligent control systems) has been sufficiently investigated.	3.83	4	3.90
Sophisticated planning tools are already developed (cross-domain, fully dynamic analysis).	3.71	4	4.00
Renovation costs for buildings have been sufficiently investigated.	4	4	4.00
Alternative options to avoid Legionella growth in domestic hot water have been sufficiently investigated (e.g., infrared cleaning, apartment substations instead of central hot water supply).	4	4	4.00
Load forecasting methods have been sufficiently investigated (e.g., based on artificial intelligence techniques).	4.21	4	4.17
The impact of increasing pump energy demand caused by a lower temperature difference between supply and return temperature has been sufficiently investigated.	4.33	4	4.36

Table 7. Statistical analysis of the answers of practitioners.

	Mean	Median	Interp. Median
Regulatory frameworks for 4GDH are already developed (e.g., bans of oil and gas boilers, CO_2 taxes...).	3.31	2.5	2.50
Construction standards have been given thorough consideration as a means of avoiding peak demands (e.g., by integrating storage mass into buildings).	3.40	3	3.00
User confidence in new technology has been sufficiently investigated.	3.60	4	3.00
Sophisticated planning tools have already been developed (cross-domain, fully dynamic analysis).	3.73	4	3.33
Facilitating active consumer participation has been sufficiently investigated (e.g., via mobile applications, gamification).	3.80	4	3.67
The impact of temperature errors in district heating systems has been sufficiently investigated (e.g., substations generating too high return temperatures).	3.87	4	3.80
Smart metering (with intelligent control systems) has been sufficiently investigated.	3.87	5	4.40
Load forecasting methods have been sufficiently investigated (e.g., based on artificial intelligence techniques).	4	4	4.00
User behavior has been sufficiently investigated (e.g., increasing comfort standard).	4	4	4.13
Sophisticated control tools have already been developed (cross-domain, fully dynamic analysis; predictive control algorithms).	4.07	4	4.13
Alternative options to avoid Legionella growth in domestic hot water have been sufficiently investigated (e.g., infrared cleaning, apartment substations instead of central hot water supply).	4.27	4	4.20
Renovation costs for buildings have been sufficiently investigated.	4	5	4.33
The impact of increasing pump energy demand caused by a lower temperature difference between supply and return temperature has been sufficiently investigated.	4.47	5	4.67

As can be seen, all values are in the range between *Mostly disagree* and *Somewhat agree*. The statement with the highest rate of disagreement is the one concerning regulatory frameworks (academic experts: $IM = 2.23$; practical experts: $IM = 2.50$). Work has recently been done on the regulatory frameworks for district heating systems (see e.g., [52–54]). The results of the survey indicate that more research is required in the field of regulatory frameworks for district heating systems.

The statement with the highest rate of agreement concerns the possible increase in pump energy demand, which covers a relatively technical topic. It implies that, according to the interviewed experts, this subject has already been sufficiently included in 4GDH analyses (see, e.g., [55–57]). The rate of agreement that user confidence in the new technology has to be further investigated was relatively high among academic experts ($IM = 2.5$), which could be a starting point for further research. The IM for the remaining statements is in the range between 3.00 and 4.30; no clear trend can be derived from these results.

4. Conclusions

This paper presents an expert assessment of 4GDH. A group of 41 experts from academia, industry, and public administration participated in a two-stage empirical survey resulting in a quantitative assessment of strengths, weaknesses, opportunities, and threats of the 4GDH together with an evaluation of the research needs in this field. The main findings from this survey are:

- Positive factors, i.e., strengths and opportunities, are considered to be more important than their negative counterparts, weaknesses and threats.
- Both academic and practical experts assigned the same two elements the highest global importance, with a difference only in the order they assigned to them. While academic experts consider the factor *"label promoting future developments in district heating"* to be the most important, the practitioner experts considered *"value creation within the national economy"* as most important. The authors consider the introduction of a 5th generation to be inappropriate at the present time.
- The most important research needs identified by the experts are in the field of regulatory frameworks.

The results of this research can be used as a basis for a purely deductive study in which different hypotheses can be tested with a larger sample. A similar study with experts would be interesting, who do not work in the area of 4 GDH systems but have expertise in the area of district heating or smart cities.

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Appendix A

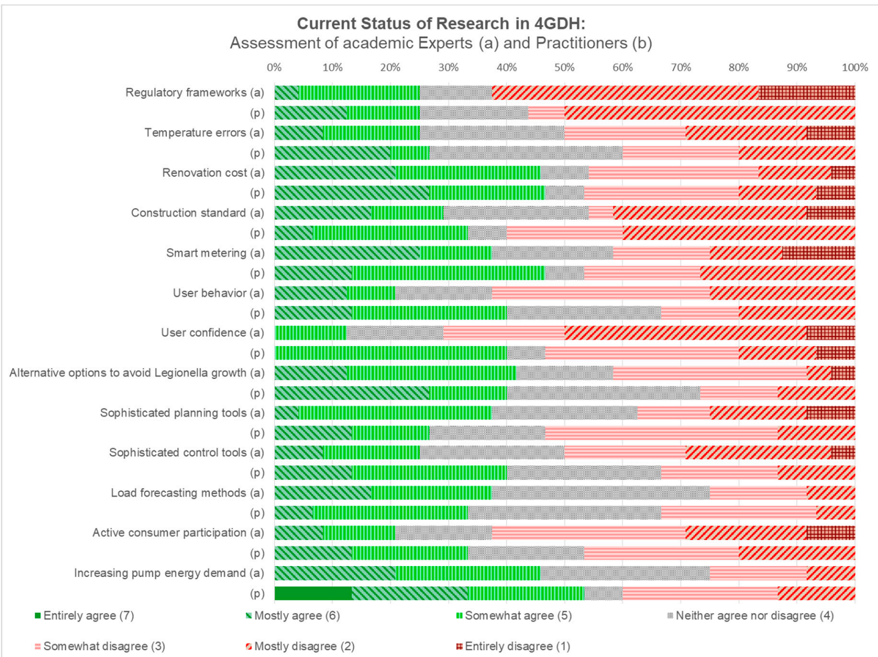

Figure A1. Current Status Research in 4GDH: Assessment of academic Experts (a) and Practitioners (p).

Appendix B

SWOT Factors:

- [S_a]: It supports sector coupling by the integration of the electricity, heating, cooling, and transport sectors
- [S_b]: It serves as a label that bundles and stimulates considerations about the future development of district heating
- [S_c]: It contributes to the decarbonization of the heating sector by using high shares of renewable energy sources and waste heat from processes in industry and commercial buildings
- [W_a]: Direct supply of domestic hot water without additional heating or other water disinfection methods is not possible (due to regulations concerning Legionella bacteria)
- [W_b]: Lacks cost efficiency in the short and middle term
- [W_c]: Difficult adaption of existing district heating networks especially in densely settled areas
- [O_a]: Value creation within the national economy due to the use of local resources
- [O_b]: Tendency to low-temperature heating systems in new buildings
- [O_c]: District heating plays an important role in the heating and cooling strategy of the European Commission
- [T_a]: Decreasing heating demand (through thermal insulation, passive houses, active houses . . .)
- [T_b]: Competitive technologies becoming more attractive (e.g., heat pumps)
- [T_c]: Existing heat supply contracts which guarantee the consumer a specific supply temperature

References

1. IPCC. *Global Warming of 1.5 °C An. IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*; IPCC: Geneva, Switzerland, 2018.
2. European Commission. *Energy Union Package—A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*; COM(2015) 80 Final; European Commission: Brussels, Belgium, 2015; pp. 1–21.
3. Fleiter, T.; Elsland, R.; Rehfeldt, M.; Steinbach, J.; Reiter, U.; Catenazzi, G.; Jakob, M.; Rutten, C.; Harmsen, R.; Dittmann, F.; et al. EU Profile of heating and cooling demand in 2015. *Heat Roadmap Eur.* **2017**, *3*.
4. Lund, H.; Andersen, A.N.; Østergaard, P.A.; Mathiesen, B.V.; Connolly, D. From electricity smart grids to smart energy systems—A market operation based approach and understanding. *Energy* **2012**, *42*, 96–102. [CrossRef]
5. Schmidt, D. Low Temperature District Heating for Future Energy Systems. *Energy Procedia* **2018**, *149*, 595–604. [CrossRef]
6. Lund, H.; Werner, S.; Wiltshire, R.; Svendsen, S.; Thorsen, J.E.; Hvelplund, F.; Mathiesen, B.V. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. *Energy* **2014**, *68*, 1–11. [CrossRef]
7. Lake, A.; Rezaie, B.; Beyerlein, S. Review of district heating and cooling systems for a sustainable future. *Renew. Sustain. Energy Rev.* **2017**, *67*, 417–425. [CrossRef]
8. Nord, N.; Nielsen, E.K.L.; Kauko, H.; Tereshchenko, T. Challenges and potentials for low-temperature district heating implementation in Norway. *Energy* **2018**, *151*, 889–902. [CrossRef]
9. Tunzi, M.; Østergaard, D.S.; Svendsen, S.; Boukhanouf, R.; Cooper, E. Method to investigate and plan the application of low temperature district heating to existing hydraulic radiator systems in existing buildings. *Energy* **2016**, *113*, 413–421. [CrossRef]
10. Tian, Z.; Zhang, S.; Deng, J.; Fan, J.; Huang, J.; Kong, W.; Perers, B.; Furbo, S. Large-scale solar district heating plants in Danish smart thermal grid: Developments and recent trends. *Energy Convers. Manag.* **2019**, *189*, 67–80. [CrossRef]
11. Popovski, E.; Aydemir, A.; Fleiter, T.; Bellstädt, D.; Büchele, R.; Steinbach, J. The role and costs of large-scale heat pumps in decarbonising existing district heating networks—A case study for the city of Herten in Germany. *Energy* **2019**, *180*, 918–933. [CrossRef]

12. Dahash, A.; Ochs, F.; Janetti, M.B.; Streicher, W. Advances in seasonal thermal energy storage for solar district heating applications: A critical review on large-scale hot-water tank and pit thermal energy storage systems. *Appl. Energy* **2019**, *239*, 296–315. [CrossRef]
13. Hast, A.; Rinne, S.; Syri, S.; Kiviluoma, J. The role of heat storages in facilitating the adaptation of district heating systems to large amount of variable renewable electricity. *Energy* **2017**, *137*, 775–788. [CrossRef]
14. Watson, J.; Gross, R.; Ketsopoulou, I.; Winskel, M. The impact of uncertainties on the UK's medium-term climate change targets. *Energy Policy* **2015**, *87*, 685–695. [CrossRef]
15. Zaunbrecher, B.S.; Arning, K.; Falke, T.; Ziefle, M. No pipes in my backyard?: Preferences for local district heating network design in Germany. *Energy Res. Soc. Sci.* **2016**, *14*, 90–101. [CrossRef]
16. Paiho, S.; Saastamoinen, H. How to develop district heating in Finland? *Energy Policy* **2018**, *122*, 668–676. [CrossRef]
17. Lygnerud, K. Challenges for business change in district heating. *Energy. Sustain. Soc.* **2018**, *8*, 20. [CrossRef]
18. Li, H.; Sun, Q.; Zhang, Q.; Wallin, F. A review of the pricing mechanisms for district heating systems. *Renew. Sustain. Energy Rev.* **2015**, *42*, 56–65. [CrossRef]
19. Cirule, D.; Pakere, I.; Blumberga, D. Legislative Framework for Sustainable Development of the 4th Generation District Heating System. *Energy Procedia* **2016**, *95*, 344–350. [CrossRef]
20. Elsevier (Ed.) *Scopus*. 2019. Available online: https://www.scopus.com/ (accessed on 1 April 2019).
21. Mayring, P. Qualitative Content Analysis. *Companion Qual. Res.* **2004**, *1*, 159–176.
22. Saaty, T.L. *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World*, 3rd ed.; RWS Publications: Pittsburgh, PA, USA, 1999.
23. Posch, A.; Brudermann, T.; Braschel, N.; Gabriel, M. Strategic energy management in energy-intensive enterprises: A quantitative analysis of relevant factors in the Austrian paper and pulp industry. *J. Clean. Prod.* **2015**, *90*, 291–299. [CrossRef]
24. Brudermann, T.; Mitterhuber, C.; Posch, A. Agricultural biogas plants—A systematic analysis of strengths, weaknesses, opportunities and threats. *Energy Policy* **2015**. [CrossRef]
25. Reinsberger, K.; Brudermann, T.; Hatzl, S.; Fleiß, E.; Posch, A. Photovoltaic diffusion from the bottom-up: Analytical investigation of critical factors. *Appl. Energy* **2015**. [CrossRef]
26. Schweiger, G.; Gomes, C.; Engel, G.; Hafner, I.; Schoeggl, J.; Posch, A.; Nouidui, T. An empirical survey on co-simulation: Promising standards, challenges and research needs. *Simul. Model. Pract. Theory* **2019**, *95*, 148–163. [CrossRef]
27. Schweiger, G.; Nilsson, H.; Schoeggl, J.; Birk, W.; Posch, A. Modeling and simulation of large-scale systems: A systematic comparison of modeling paradigms. *Appl. Math. Comput.* **2020**, *365*, 124713. [CrossRef]
28. Saaty, T.L. Axiomatic Foundation of the Analytic Hierarchy Process. *Manag. Sci.* **1986**, *32*, 841–855. [CrossRef]
29. Hallowell, M.R.; Gambatese, J.A. Qualitative Research: Application of the Delphi Method to CEM Research. *J. Constr. Eng. Manag.* **2010**, *136*, 99–107. [CrossRef]
30. Sachs, L. *Angewandte Statistik*; Springer: Berlin/Heidelberg, Germany, 1997.
31. Hedderich, J.; Sachs, L. *Angewandte Statistik Methodensammlung mit R*, 14th ed.; Springer: Berlin/Heidelberg, Germany, 2012.
32. Lund, H.; Østergaard, P.A.; Chang, M.; Werner, S.; Svendsen, S.; Sorknæs, P.; Thorsen, J.E.; Hvelplund, F.; Mortensen, B.O.G.; Mathiesen, B.V.; et al. The status of 4th generation district heating: Research and results. *Energy* **2018**, *164*, 147–159. [CrossRef]
33. Schweiger, G.; Rantzer, J.; Ericsson, K.; Lauenburg, P. The potential of power-to-heat in Swedish district heating systems. *Energy* **2017**, *137*, 661–669. [CrossRef]
34. Yang, X.; Li, H.; Svendsen, S. Decentralized substations for low-temperature district heating with no Legionella risk, and low return temperatures. *Energy* **2016**, *110*, 65–74. [CrossRef]
35. Zhang, X.; Strbac, G.; Teng, F.; Djapic, P. Economic assessment of alternative heat decarbonisation strategies through coordinated operation with electricity system—UK case study. *Appl. Energy* **2018**, *222*, 79–91. [CrossRef]
36. Gerres, T.; Ávila, J.P.C.; Llamas, P.L.; Román, T.G.S. A review of cross-sector decarbonisation potentials in the European energy intensive industry. *J. Clean. Prod.* **2019**, *210*, 585–601. [CrossRef]
37. Frederiksen, S.; Werner, S. *District Heating and Cooling*; Studentlitteratur: Lund, Sweden, 2013.
38. EC. *An EU Strategy on Heating and Cooling (COM(2016) 51 Final)*; EC: Brussels, Belgium, 2016.

39. Ziemele, J.; Cilinskis, E.; Blumberga, D. Pathway and restriction in district heating systems development towards 4th generation district heating. *Energy* **2018**, *152*, 108–118. [CrossRef]
40. Park, C.; Jeong, Y.; Yoo, S.J. A study of consumer benefit from district heating service in Korea. *Energy Policy* **2019**, *129*, 958–966. [CrossRef]
41. Valodka, I.; Valodkienė, G. The Impact of Renewable Energy on the Economy of Lithuania. *Procedia-Soc. Behav. Sci.* **2015**, *213*, 123–128. [CrossRef]
42. Martin, M.; Røyne, F.; Ekvall, T.; Moberg, Å. Life Cycle Sustainability Evaluations of Bio-Based Value Chains: Reviewing the Indicators from A Swedish Perspective. *Sustainability* **2018**, *10*, 547. [CrossRef]
43. 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*, 45–60.
44. Averfalk, H.; Werner, S. Novel low temperature heat distribution technology. *Energy* **2018**, *145*, 526–539. [CrossRef]
45. Rønneseth, Ø.; Sandberg, N.H.; Sartori, I. Is It Possible to Supply Norwegian Apartment Blocks with 4th Generation District Heating? *Energies* **2019**, *12*, 941. [CrossRef]
46. Averfalk, H.; Werner, S. Essential improvements in future district heating systems. *Energy Procedia* **2017**, *116*, 217–225. [CrossRef]
47. Vivian, J.; Emmi, G.; Zarrella, A.; Jobard, X.; Pietruschka, D.; de Carli, M. Evaluating the cost of heat for end users in ultra low temperature district heating networks with booster heat pumps. *Energy* **2018**, *153*, 788–800. [CrossRef]
48. Grundahl, L.; Nielsen, S.; Möller, B. Comparison of district heating expansion potential based on consumer-economy or socio-economy. *Energy* **2016**, *115*, 1771–1778. [CrossRef]
49. European Commission. *Energy 2020—A Strategy for Competitive, Sustainable and Secure Energy*; European Commission: Brussels, Belgium, 2011.
50. Buffa, S.; Cozzini, M.; D'Antoni, M.; Baratieri, M.; Fedrizzi, R. 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renew. Sustain. Energy Rev.* **2019**, *104*, 504–522. [CrossRef]
51. Boesten, S.; Ivens, W.; Dekker, S.C.; Eijdems, H. 5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply. *Adv. Geosci.* **2019**, *49*, 129–136. [CrossRef]
52. Skytte, K.; Olsen, O.J. Regulatory barriers for flexible coupling of the Nordic power and district heating markets. In Proceedings of the 2016 13th International Conference on the European Energy Market (EEM), Porto, Portugal, 6–9 June 2016; pp. 1–5.
53. Skytte, K.; Olsen, O.J.; Soysal, E.R.; Sneum, D.M. Barriers for district heating as a source of flexibility for the electricity system. *J. Energy Mark. Forthcom.* **2017**, *10*, 1–19. [CrossRef]
54. Werner, S. District heating and cooling in Sweden. *Energy* **2017**, *126*, 419–429. [CrossRef]
55. Best, I.; Orozaliev, J.; Vajen, K. Impact of Different Design Guidelines on the Total Distribution Costs of 4th Generation District Heating Networks. *Energy Procedia* **2018**, *149*, 151–160. [CrossRef]
56. Averfalk, H.; Ottermo, F.; Werner, S. Pipe Sizing for Novel Heat Distribution Technology. *Energies* **2019**, *12*, 1276. [CrossRef]
57. Nussbaumer, T.; Thalmann, S. Influence of system design on heat distribution costs in district heating. *Energy* **2016**, *101*, 496–505. [CrossRef]