The status of 4th generation district heating

Research and results

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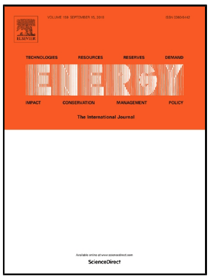

The Status of 4th Generation District Heating: Research and Results

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Review

The Status of 4th Generation District Heating: Research and Results

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Highlights:

- Provides a review of 4th Generation District Heating (4GDH) in scientific papers
- Shows how 4GDH is an important integrated part of future sustainable energy systems
- Quantifies costs and benefits of 4GDH in a future sustainable energy system
- Shows how benefits exceed costs by a safe margin
- Shows the significant benefits of systems integration

Abstract

This review article presents a description of contemporary developments and findings related to the different elements needed in future 4th generation district heating systems (4GDH). Unlike the first three generations of district heating, the development of 4GDH involves meeting the challenge of more energy efficient buildings as well as the integration of district heating into a future smart energy system based on renewable energy sources. Following a review of recent 4GDH research, the article quantifies the costs and benefits of 4GDH in future sustainable energy systems. Costs involve an upgrade of heating systems and of the operation of the distribution grids, while benefits are lower grid losses, a better utilization of low-temperature heat sources and improved efficiency in the production compared to previous district heating systems. It is quantified how benefits exceed costs by a safe margin with the benefits of systems integration being the most important.

Keywords: *4th generation district heating; 4GDH; low-temperature district heating; smart energy systems; smart thermal grids; meta conclusions.*

Abbreviations

3GDH	3rd generation district heating
4GDH	4th generation district heating
CHP	Cogeneration of heat and power
COP	Coefficient of performance

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DH	District heating
DHW	Domestic hot water
RE	Renewable energy
TRV	Thermostatic radiator valve

Contents

1 Introduction

The transition from current energy systems to future sustainable energy solutions, including 100 per cent renewable energy (RE) systems, requires a coherent approach that integrates the different components of the energy system and exploits synergies through sector integration [1–3]. District heating and cooling can have an important role to play in such systems, but the technologies must undergo a generational shift for their potentials to be fully exploited [4–7].

Unlike the previous three generations, the development of *4th Generation District Heating* (4GDH) – as defined in [6] – involves balancing the energy supply with energy conservation and thus meeting the challenge of supplying increasingly more energy efficient buildings with space heating and domestic hot water (DHW), while reducing losses in district heating (DH) grids. Furthermore, 4GDH involves strategic and innovative planning and the integration of DH into the operation of smart energy systems such as defined in [8].

The following review refers to a definition paper [6] in which the purpose was to define the concept of 4GDH including the concept of Smart Thermal Grids and thereby contribute to the understanding of the need for research and development of such future infrastructure and related technologies.

The paper defined the 4GDH system as a coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems. 4GDH systems supply heat to low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated into the operation of smart energy systems. The concept involves the development of institutional and organisational frameworks with appropriate cost and incentive structures [6].

In order to be able to fulfil its role in future sustainable energy systems, DH will need to have the following abilities (See also Figure 1):

1. The ability to operate existing, renovated and new buildings with low-temperature DH for space heating and DHW.
2. The ability to distribute heat in networks with low grid losses.
3. The ability to recycle heat from low-temperature sources and integrate renewable heat sources such as solar and geothermal heat.
4. The ability to be an integrated part of smart energy systems and thereby helping to solve the task of integrating fluctuating renewable energy sources and energy conservation into the smart energy system.
5. The ability to ensure suitable planning, cost and incentive structures in relation to the operation as well as to strategic investments related to the transformation into future sustainable energy systems.

Figure 2 shows an overview of the future 4GDH compared to the previous three generations. This is further detailed in [6]. The previous generations were developed when buildings had high heat demands and high DH temperature requirements and when the heat supply was based on fossil fuels. The new fourth generation is required for future DH systems based on non-fossil heat sources and delivering heat to buildings with low heat demands. Figure 2 is an up-dated version of a diagram previously published in [6]. In this version, more elements are added and the temperature levels have been futher detailed.

This review paper presents a description of contemporary developments and findings related to the different elements needed in future 4GDH systems. First, an overview of the status of the 4GDH concept in academic literature is presented. Then, 4GDH building systems and distribution grids are described, followed by a discussion of 4GDH in smart energy systems and heat sources for 4GDH. An overview of approaches, costs and incentive structures is presented in relation to the operation of 4GDH systems as well as to strategic investments related to the planning and implementation of 4GDH in future sustainable energy systems. Finally, this leads into a discussion and summary of the cost and benefits of the transition towards 4GDH.

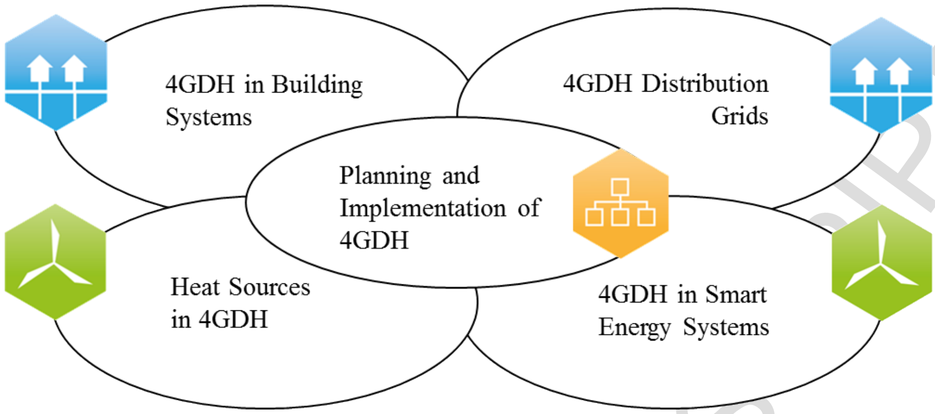

Figure 1: Essential elements of the concept of 4GDH - updated version based on [6].

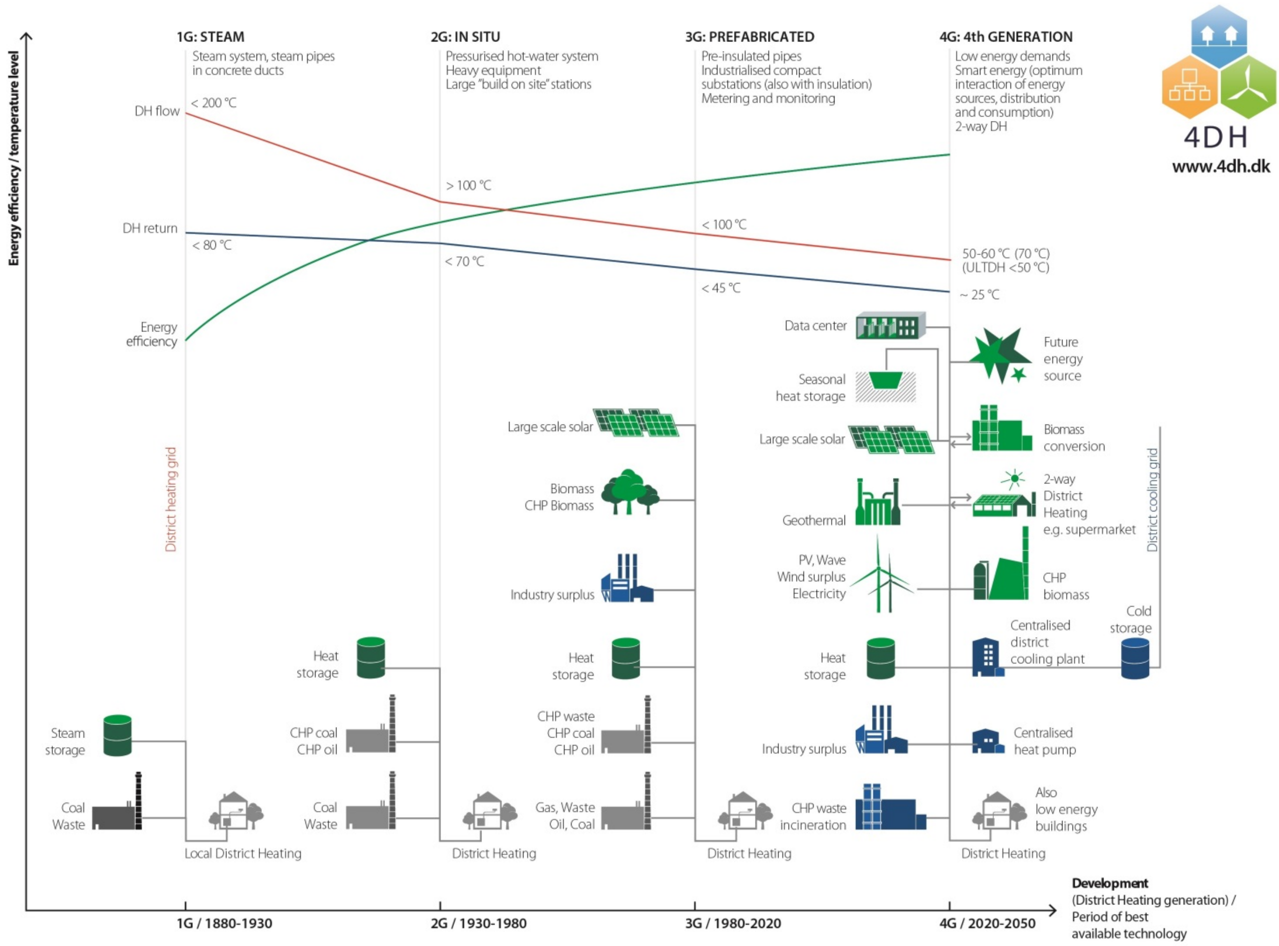

Figure 2: The concept of 4GDH compared to previous DH generations [9] *updated version based on* [6].

2 Status of 4GDH in the literature

The concept of 4GDH has gained strong momentum in the academic literature since being defined in [6] in 2014. A search in academic research databases of the term "4th generation district heating" has been conducted, limiting the search to research journal articles, conference papers, review papers and editorials. In Scopus, 321 papers have been identified up until and including the year 2017 that met this search criterion, while a further query shows that out of these, 19 papers explicitly mention the term in their title, abstract or keywords. Similarly, 463 papers were identified in ScienceDirect in a full-text search, with 20 papers explicitly using the term in their title, abstract or keywords. Google Scholar yielded a total of 561 search results, including non-journal articles. Several overlapping results were identified in these searches, with some papers only using the term in passing, or citing, among others, the concept definition by [6]. For the analysis, those papers with active use of the term or those referring or alluding to the elements of the 4GDH concept outlined in Figure 1 have been used, as well as papers where the term occurs in references while addressing some of the terms in Figure 1. This survey included a total of 298 publications.

The overview of this survey, presented in Figure 3, shows the publication count of papers using or alluding to the 4GDH concept. As seen, since 2014, the 4GDH concept has become increasingly used. This is most notable in connection to 4GDH in Smart Energy Systems (SES) and cross-sectoral and renewable energy integration. A separate category was identified in this survey, encompassing those papers with direct connection to 4GDH, but which did not necessarily fit within the elements of Figure 1. This category included papers with main topics relating to historical developments leading to 4GDH, operation strategies including real time balance between heat supply and demand, monitoring of specific system components, description and reviews of specific technologies, environmental analyses, and specific modelling approaches suggested for 4GDH.

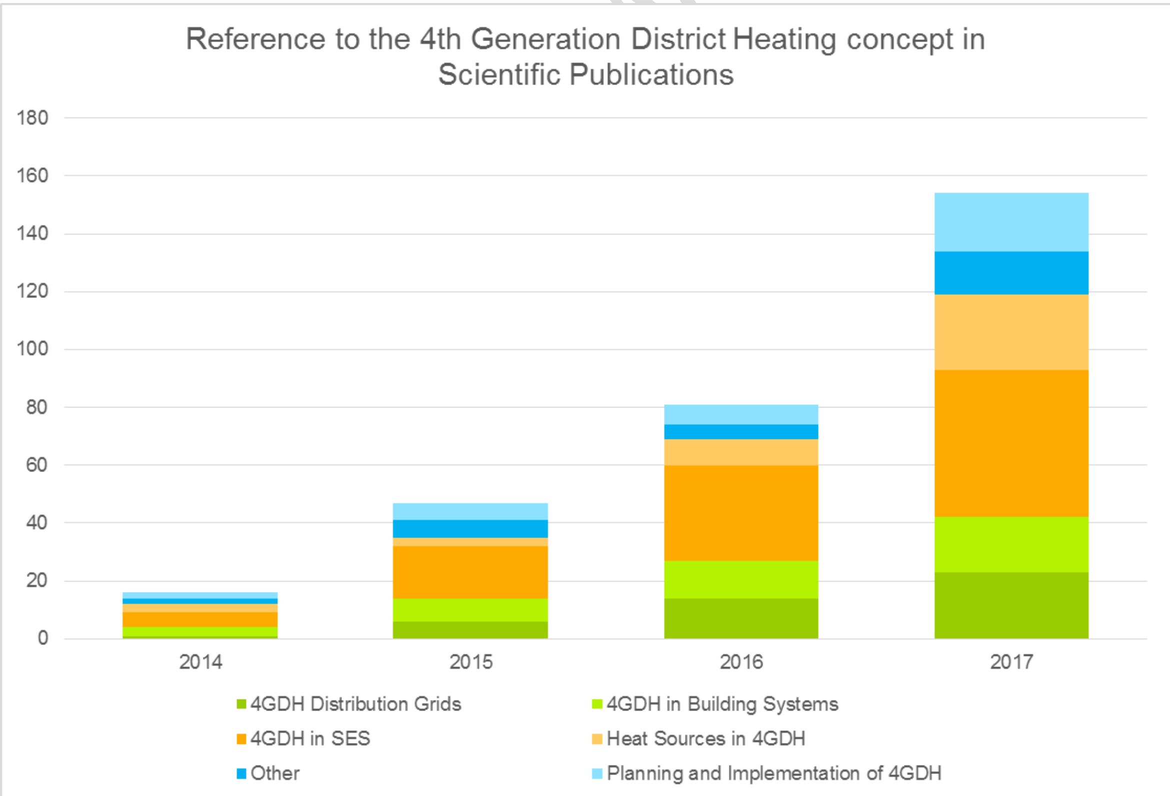

Figure 3: Overview of the "4th generation district heating" concept as referenced in the scientific literature up until the year 2017. The categories outline the main focus of these papers in relation to the elements

presented in Figure 1, without accounting for overlapping themes and topics. The "Other" category denotes papers that, although alluding to 4GDH, present topics outside the scope of the concept.

3 4GDH in building systems

The transition towards 4GDH should follow a step-wise approach involving first the lowering of the return temperature and, secondly, the lowering of the supply temperature in the system. This entails developing and testing solutions at the building level with relevant types of systems for space heating, DHW supply, building renovations and new components such as substations or booster heat pumps if needed. Parallel to the implementation of low return and supply temperatures in the buildings, the DH networks and heat producing systems should be changed to make sure that the potential benefits of low temperatures are realized in the operation of the networks and the heat production systems [5]. The lowering of temperature levels system-wide has shown to be a key to large cost reductions in future energy systems [10].

3.1 Space heating by low-temperature DH

Heating systems are typically designed for a heat demand based on worst-case scenario. The actual heat demand of the building during the full heating season is typically in the range of 0-80% of the design heat demand, meaning that the maximum demand is 80%, but may be as low as 0% at the beginning and the end of the heating season. Therefore, the radiators and heat exchangers of the existing heating system will be able to deliver the actual part load with lower temperatures than the design temperatures.

Recent studies have shown a large potential for lower DH temperatures through an improved performance of the space heating system in existing buildings from different construction periods [11], as seen in analyses of Danish single-family houses from the 1930s [12], 1950s [13], and 1980s [14]. These improvements can be achieved by targeting the control system of the heating system in the existing building stock which affects return and supply temperatures.

For instance, in the case of typical Danish single-family houses, it has been demonstrated that, after renovations of building components and the implementation of energy-efficiency measures, the existing buildings can be heated with lower temperatures throughout large parts of the year. This requires a proper design of radiator systems [11] though. With properly designed heating systems, the general supply temperature in existing buildings with radiators can be as low as 45°C [14].

In those buildings in which radiator systems are not sufficiently large for low-temperature heating, the replacements of 'critical' radiators with larger ones have proved to ensure thermal comfort and enable lower supply and return temperatures of approximately 50°C and 27°C, respectively. In the case of insufficient radiator size, it is possible to provide additional flexibility by increasing the DH supply at peak demand periods [12]. The replacement of radiator systems should not be limited to targeting radiator size, but also other problem areas. For instance, one-string pipe connections to radiators should be phased out and converted to two-string connections to prevent return and supply flows to mix; thus, allowing low return temperatures and smaller pipe dimensions. Similarly, where possible, low-panel and convector radiators should be replaced with high-panel radiators, which have a better water flow stratification and generally achieve lower return temperatures than low-panel radiators with similar heating power [15]. Moreover, control systems, which typically consist of a central supply temperature controller and a thermostatic radiator valve (TRV) on each radiator, should additionally include combined control-based TRVs with both a room temperature sensor and a radiator return temperature sensor with the aim to keep a low return temperature when reheating rooms to set-point temperature [15]. In turn, this can provide a more efficient operation of the heating system by reducing the risk of poor use and its effects on the control system [16].

Meanwhile, simulation models have proved to assist in identifying the optimal reduction in supply and return temperatures [16], provided that accurate representations are made of actual radiator sizes and indoor temperature set-points [17]. The implementation of newer electronic TRVs with room temperature sensors could potentially provide additional data for making more accurate representations of the systems, as well as improved control [15]. New buildings are typically heated by floor heating systems and are therefore well-suited for low-temperature operation.

3.2 Supply of domestic hot water (DHW) in low-temperature DH systems

Comfort temperatures in the DHW supply can be achieved with low-temperature DH [18–21]. For this, DHW solutions in 4GDH systems must meet some basic requirements, which include setting a maximum waiting time of 10 seconds for tap water and comfort temperatures between 40°C and 45°C, as well as Legionella-safe temperatures of 50-55°C in circulation lines, any storage tanks and in centrally placed instantaneous DHW heat exchangers [22–24]. With the use of a DHW heat exchanger without storage (instantaneous heat exchangers), these issues are less critical. Energy system analyses recommend to decrease forward district temperatures to the point where boosting is required, i.e. to approximately 55°C, and to avoid the extra costs of individual units within each household [10].

Effective DHW temperature boosting in existing buildings equipped with storage tanks and circulation lines can be provided by easy-to-install and affordable solutions such as electric heat tracing systems, i.e., electric heating provided by cables wounded around supply pipes, when full renovations of the pipe network are not feasible or when there are space limitations [19], and by electric heating elements [24]. However, the feasibility of such a solution may in many places be limited due to high electricity prices.

In the case of a DHW storage tank, the heating of the DHW storage is controlled by measuring the temperature in the upper half of the tank; if the temperature is too low, a valve is opened for the DH water to circulate in a heat exchanger coil in the tank. Often, the valve is over-sized even for very high DHW use. Accordingly, the performance of the storage tank can be improved by controlling based on the measured use of DHW and reheating the tank with a low-temperature flow [21]. Anyhow, this solution is more to be seen as a temporary solution, whereas instantaneous heat exchangers are more obvious for DHW applications in 4GDH.

In the case of new buildings, DHW can be provided locally by decentralized substation systems with instantaneous heat exchanger units [18,22], the so-called flat station concept. In the case of renovation of the space heating and DHW system for older buildings, the flat station concept can be an attractive solution. Likewise, micro heat pump or electricity temperature booster systems can also be applicable in new low-energy buildings and single-family houses [24].

The heat supplied to the substations in each flat can be made by one heating loop that replaces the conventional two loops for space heating and circulation of DHW, thus providing better performance. During summer periods with limited or no space heating demand, the DHW supplied by the heat exchanger can be kept warm by a continuous flow for heating bathroom floors [25]. By implementing flat station concepts for multi-family houses or individual stations for single-family houses in low-temperature DH, savings of up to 30% can be achieved in the annual distribution heat loss inside the buildings, when compared to a conventional central system with separate distributions of space heating and DHW. In addition, the bypass pipe can be replaced by an in-line supply pipe and a heat pump, leading to savings of up to 39% [18].

One important element aiming for low DH temperatures is the thermal length of the applied heat exchangers, for heating as well as for DHW. Analysis and case example show that it is beneficial to increase the thermal length by a factor 2, approximately, compared to what is typically applied today [26,27].

4 4GDH Grids

This section details the impacts of 4GDH on DH grids, grid losses and grid expansion.

4.1 Conversion of DH grids to low-temperature and grid expansion

In general, the capacity requirements to the pipes and to the pumping capacity within DH grids remain unchanged when a reduction in the supply temperature is accompanied by the same reduction in the return temperature. When this is the case, the same amount of heat can be supplied in the existing pipes at a lower supply temperature and at approximately the same pumping power consumption.

DH grid systems most often follow a radial or a tree structure – consisting of transmission pipes with distribution pipes branching out. The tree structure is suitable for systems with a central heat source at a fixed location and without any expansion coverage in the direction/area of the transmission line. Analyses examining changes in these systems show that open source computational models can be valuable tools for simulating the thermal performance of the DH grid in the case of variations in heat consumption and/or heat production. The models can be useful for modelling energy systems with multiple heat sources and energy optimization of the heat consumption [28]. In a similar manner, the use of a genetic algorithm applied to finding an optimal DH network configuration with respect to pipe connections and the position of the plants can be used for assessing the conversion and expansion of DH networks [29] and optimal placement of storage[30].

When more heat sources are available at different geographical locations, capacity limitations might occur in the abovementioned tree structure. Thus, to ensure a flexible supply of DH, other DH grid layouts can be considered. An alternative could be a ring structure –where the DH network is laid out as a main loop in a chosen area with branches reaching all consumers– with optional future expansion to new heat sources and new DH consumers anywhere along the loops [31].

4.2 Minimizing DH grid losses

In the existing DH grid, heat losses can be reduced by reducing operating temperatures; supply and return temperatures. Furthermore, a dynamic optimization of the DH operation is expected to contribute to a reduction of the heat losses and to the pumping power requirements.

When new pipes are installed to replace or extend the existing grids, the grid losses can be reduced by increasing the pipe insulation thickness, by using twin or triple pipes, by optimizing/minimizing the pipe dimensions and by an alternative routing layout of the pipes.

Figure 4: Double DH pipe system by Logstor.

For service connection pipes, connecting street distribution DH lines to dwellings, optimally designed double pipe systems as shown in Figure 4 can reduce losses by 6–12%, over traditional twin pipe configurations with no increase in investment costs [32]. Also, triple pipe solutions have been discussed in relation to low-energy and future applications [32,33] in order to achieve very low return temperatures. The routing layout of DH systems is normally not designed to minimize grid losses, but this can be accounted for by using genetic algorithms, which may identify optimal configurations of the network based on the design and operation conditions [29,30].

5 Heat Sources in 4GDH

In general, a significant amount of low-temperature sources are available for heating in most parts of the world. E.g., at the EU level, heat resources for DH [34] include waste heat from industry and data centres [35–38], power generation [39–41], and waste incineration [42]. Moreover, these sources are easy to access. For instance, 46% of the total excess heat volume in EU27 is situated in 63 strategic heat synergy regions [43].

Also at the EU level, excess heat utilization can help reduce operating hours of CHP and boilers and bring about operational cost and fuel savings [37], depending on the quality of waste heat [38]. Waste resources are significant but various trends impact their future availability to the energy sector. On the one hand, less waste is being landfilled; on the other, an increased amount of waste is planned for recycling in the future, and in ambitious recycling scenarios, only one quarter of future municipal solid waste may be available for energy recovery [42]. Similarly, increasing shares of fluctuating RE sources used for heat production and thermal storage including seasonal storage have been shown to reduce system costs [39,44,45]. Thus, DH has the possibility to play an important role with regard to decreasing the use of biomass and keeping it for other sectors, while still enabling a 100% renewable energy system [46].

In individual countries such as, e.g., Denmark, low-temperature heat resources in combination with heat pumps for temperature boosting are available to DH [47–49], although resources of a higher temperature than ambient temperatures are limited. In the Danish case, ground water and sea water have the highest potentials, though only two-thirds of the heat demand is sufficiently close to the sea [50].

In current energy systems based on fossil fuels, a substantial contribution of these sources is connected to power production from combustion. In future systems based on renewable energy, such a power production will be replaced partly by wind power and similar sources. However, new sources will arise as explained in the following.

6 4GDH in Smart Energy Systems

6.1 The role of 4GDH in national energy systems

Analyses of energy systems in Europe [43,51,60–62,52–59], Denmark [48,50,63–68], and China [69–72], show a great potential for unlocking energy savings and improving the integration of renewable energy sources.

In the study Heat Roadmap Europe [53], a strategy of DH is introduced in which district heating and individual heat pumps elsewhere are combined with heat savings of 50%. This strategy is able to accomplish the same fossil and biomass fuel consumptions as the mainly electricity-based EU energy efficiency scenario of the European Commission, but at 15% lower costs.

Similarly, analyses of the Chinese energy system have demonstrated that DH could generate a 60% reduction in the primary energy supply for heating of the Chinese building sector at 15% lower total cost (including investment costs) [69]. For Denmark, analyses show that the heat production from natural gas boilers can be replaced mainly by DH based on excess heat from the production of transport fuels and from industry in combination with the use of large-scale heat pumps. For individual houses outside the reach of DH, individual heat pumps and a small share of biomass boilers where applicable can be used in combination with a small solar thermal share. This, combined with 40% heat savings, can result in lower system costs and provide a better integration of the electricity, heating and transport sectors [63].

6.2 Integration of energy systems and production system impacts

Synergies across sectors are important to the integration of fluctuating RE sources in the future sustainable energy system. Particularly, the inclusion of the DH sectors enables the exploitation of low-cost thermal energy storage [45,73] that, combined with, e.g., DH plants and electric heat pumps, gives a potential for also integrating RE into the power system in which the simultaneity factor is particularly important. Coupling this with energy savings makes it possible to create the flexibility needed to better integrate and utilize the low-temperature energy sources needed in future DH systems [74].

To assess this flexibility and the integration in the energy system, analytical tools for energy systems simulation and analyses are required. One such tool is EnergyPLAN, which allows the handling of integration across sectors with a high temporal resolution and a high complexity of energy systems with fluctuating RE sources [75]. Additionally, systematic methodological approaches may be needed to consider different solutions and uncertainties in the design of smart energy systems [76].

In an analysis of alternative systems for cogeneration of heat and power (CHP) in the future Danish energy system, three technologies are assessed, all based on biomass. These are Advanced pulverised fuel, Combined cycle gas turbine and Circulating fluidised bed [77]. Of these, the Combined cycle gas turbine will have the lowest costs and biomass consumption; this is important when operating under a biomass availability constraint. However, the analyses also reveal that this least-cost option will not necessarily be implemented without regulatory measures.

In the Danish case, smaller sizes of CHP units are experiencing problems due to prices on the power market. If CHP plants can operate on more markets at different time horizons, and not just the Scandinavian day-ahead market, CHP becomes more profitable [66]. The operation of CHP units may be increased by 25% and heating costs may be decreased by 5% as a consequence of the participation in more markets. This is based on analyses of the DH system in the municipality of Ringkøbing-Skjern [78]. In the longer term though, fossil-fuel-based CHP units will not have a role to play; thus, they must either be switched to a synthetic fuel and operated to supply grid services or be replaced by, e.g., heat pumps and/or waste heat from various sources.

Several analyses have demonstrated that large-scale heat pumps play a large role in future RE-based energy systems. In the 4DH project, analyses have identified a potential of between 2 and 4 GW thermal capacity in the Danish heating system [49,63] and have indicated that two-thirds of the heat supply should be covered by DH and the remainder by individual heat pumps [74].

As already mentioned in section 3.2, it is recommended only to decrease forward district temperatures to the point at which boosting is required. This corresponds to approximately 55°C and means that extra costs of individual units within each household can be avoided [10].

Other analyses have applied booster heat pumps to supply domestic hot water combined with floor heating – which is already found in most new buildings in Denmark – and this enables the detachment of DH temperatures from DHW temperatures. DH temperatures down to 30-35°C may become relevant in this way, which in turn can have positive effects on efficiencies in CHP units or heat pump units in DH plants. Also, grid losses are decreased as a consequence of the lowered temperature difference between the surrounding soil and the water [79,80]. These analyses were based on individual private economic costs. The socio-economic system costs, however, may increase in such systems.

Similarly, cross-sector integration including DH has been shown to bring about further benefits to cross-border interconnection with transmission cables, since the excess electricity produced from RE can be used within the system due to higher flexibility in the system and a higher electricity demand [81].

6.3 Heat savings and energy system impacts

Several analyses have been conducted on saving potentials and energy system impacts of these as well as the potential and benefits of low-temperature district heating, including analyses at the EU level [53], at a national level (Denmark) [74], and at a local level [64]. Similarly, the roles of CHP plants [77,82] and heat pumps [47,55] have been addressed.

Heat savings play a crucial role in 4GDH systems. In an analysis defining the appropriate level of heat savings in Denmark, marginal heat production costs are compared to the marginal costs of producing DH. Based on this, it is determined that it is profitable to reduce heat demands by 50% in new buildings as well as in buildings under renovation. For buildings that would not otherwise undergo renovation, energy efficiency measures do not pay off [74]. Moreover, analyses of heat saving potentials in the Czech Republic, Croatia, Italy and Romania indicate that savings of 30-50% are optimal from an economic perspective [54].

Previous analyses have also demonstrated how heat savings affect CHP operation and thus these plants' potential for supplying ancillary services to the electricity grid[83]. Thus for future electricity systems, it becomes important that ancillary-service provision is distributed to other production and demand technologies.

7 Planning and Implementation of 4GDH

The transition towards 4GDH and smart energy systems requires innovative planning practices, support tools, policies facilitating the transformation, as well as changes in economic calculation practices. These include conducting strategic and innovative energy planning considering legal perspectives and socio-economic development, energy atlases to support the planning process, and the proposal of new price regulations and tariffs [6,84,85]. This section details some of these general public regulation, planning and framework conditions that will further 4GDH.

7.1 Public regulation and 4GDH

The implementation of 4GDH systems represents a paradigmatic shift in terms of public regulation in various aspects. With regard to heat conservation, the shift should involve the right level of public regulation of the right type at the right time. *The right level* of public regulation means that investments in the demand system must be balanced against investments in the supply system to achieve savings in both fossil fuels and investments.

At the right time means that, in a 100% RE-based 4GDH system, heat conservation will save capital investments in the supply system; and contrary to saved fuel, these supply system investments cannot be used elsewhere in the system. Society has to make energy conservation in time to avoid investment that will become sunk cost in the energy supply systems.

The right type means that heat conservation should be made in such a way that it supports the transition to 4GDH. Furthermore, the effects of heat conservation in a smart energy system have much broader system effects than heat conservation in a 3GDH system. For instance, heat conservation furthers low-temperature DH, which again increases the coefficient of performance (COP) of heat pumps and efficiency of CHP units. Consequently, the competitiveness and potential for integration of wind power are increased in the heat system. This means that the value of heat conservation is changed from heat sector-only to long-term energy system benefits. Thus, the heat tariffs should reflect the system value of heat conservation.

7.2 Strategic energy planning in a legal, socio-economic and innovative perspective

Certain parts of the legal framework under which energy systems operate can be considered a barrier to promoting DH or an abnormality to general legislation regulating the relation between a supplier and a consumer [7,86–88]. At the European level, strategic energy policies appear unbalanced with a larger weight on developing cross-country electricity markets and limited attention to developing country-internal system integration [89,90].

This unbalance is also found in well-established DH markets, like the Danish, where it can be seen in energy policy and planning. More concretely, the current regulation of the Danish energy system does not underpin the development of DH to a sufficient degree [84,91]. Thus, a renewed understanding of the merits and potentials of current policy and regulatory designs can put into focus the role of integrating DH into existing energy systems [92–94].

Moreover, a socio-economic perspective in the planning process can aid in providing a better understanding of the existing framework conditions and potential technological change [84,95]. In addition, incentives for energy savings [86], fuel efficiency in supply [95], local ownership [92], and empowerment of local actors [96] have been shown to facilitate the realization of the transition towards future 4GDH systems.

7.3 Energy atlases to support planning

A geospatial representation of heating and cooling demand and potential supply is an essential precondition of planning. Due to the local nature of thermal demand and supply, geographical information systems (GIS) with data and relevant methods are required for the evaluation of DH and cooling potentials, and in the design of strategies. Combined methodological approaches using mapping and modelling have shown to provide insight into and the ability to spatially determine and quantify local demands and resources to properly assess both future DH and cooling potentials [43,97–99] .

On a European scale, the Pan-European Thermal Atlas (Peta) provides mapping and quantification of heating and cooling demands as well as the costs of distribution grids, the availability of waste heat resources under temporal and spatial constraints, and the potentials of RE in proximity to these systems to assist in developing prospective DH infrastructures [100–103]. At a resolution of 100m grid cell size, it is unprecedented at this time.

Similarly, heat atlases used in the context of Denmark have enabled assessments of energy efficiency and the development potential of 4GDH systems for actual locations in Denmark with a single building as the smallest computation unit for which technical and economic calculations are carried out using current planning databases. The heat atlases have been used to perform studies for municipalities [67,78] and regions [97], as well as national analyses of the spatially continuous potentials for energy efficiency [104], consumer and socio-economy [65], and the expansion of DH, connected to extensive energy systems analysis [98].

7.4 4GDH in European research programmes and implementation programmes

Many European energy research projects within Horizon 2020 explore and test various 4GDH features with respect to DH grids and heat sources. During 2017, the German government initiated a national

4GDH implementation programme of 100 M EUR until 2020 to support several pre-studies and pilot schemes.

7.5 4GDH in the context of Eastern Europe

Eastern Europe has a large amount of old DH grids with 2nd generation technology involving high losses and a dominant share of fossil fuels. The challenge is how to supply existing buildings efficiently and sustainably within this context. 4GDH offers a solution in these cases but the implementation will face additional barriers. These can simply be summed up as:

1. Inefficient buildings designed to operate with high heat supply temperatures,
2. Large centralized networks,
3. Reliance on combustion technologies, mainly based on fossil fuels.

Since a simultaneous refurbishment of the entire building stock is infeasible here, as in other areas of the world, a modular approach is necessary. A step by step refurbishment method focused on districts at branches of the DH network that can be isolated could be applied. By refurbishing such a district or a group of buildings, the supply temperature can be reduced and pipes in the corresponding section can be retrofitted with 3GDH and 4GDH. The grid as such would supply high temperature heat to satisfy all of the existing users, but in this case, a substation can be introduced to the isolated branch which would function as a virtual DH plant supplying 4GDH level temperatures. As such, it would use the heat from the network as a source and distribute it at a lower temperature to this isolated district. By doing this, low-temperature RE, and excess heat if available, could be introduced in this part of the network.

This concept can be expanded modularly through a given city as refurbishment efforts are conducted in other districts. When the majority of the buildings are refurbished in such a way, the concept can be switched and the entire network can supply low-temperature DH.

8 Comparison between 3GDH and 4GDH

In order to assess the technical and economic advantages and disadvantages of 4GDH systems compared to 3GDH systems, this section presents a comparison of the two approaches in a national-scale energy system.

The overall idea of the assessment is to define a context representing a future sustainable energy system and then assess the cost and benefits of replacing 3GDH by 4GDH. The overall structure of the assessment is composed by an estimate of the following elements:

- Additional cost at the building level of a low-temperature supply
- Additional cost in the DH grid to be able to supply 4GDH
- Savings in the DH grid due to lower temperatures
- Savings in the production (system costs) due to lower temperatures.

The two first elements can be calculated separately based on the inputs mentioned in the previous sections. However, by nature, the two latter elements have to be calculated together since they constitute an integrated part of the system costs. In order to be able to calculate the benefits, one has to define the overall energy systems and apply detailed energy systems analysis tools to clarify how a change from 3GDH into 4GDH influences the cost of the system. Such influence includes, e.g., a more efficient use of heat pumps and CHP plants and thereby has consequences for the electricity supply and the integration of wind as well as the fuel balance and thereby the use of biomass.

The analysis takes its point of departure in a future national energy system based on the principles of smart energy systems, i.e., a system based on RE in combination with energy efficiency and a cross-sectoral approach as explained in the previous sections. For practical reasons, a proposal for Denmark in the year 2050 has been used. However, in principle it could be many other countries including countries that have no or very little DH today.

This comparison follows a short introduction to the energy systems simulation model EnergyPLAN and an introduction to the case and scenario design in which the savings have been calculated. Then an assessment of the buildings and grid costs is added and a final comparison is made.

8.1 Energy system simulations using EnergyPLAN

EnergyPLAN is an hourly energy systems simulation model designed to simulate and to optimise through exogenous inputs the design of energy systems based on high degrees of RE. The model is based on analytical programming, where system responses to predefined circumstances are coded into the simulation algorithms. The model is originally created to simulate the interplay across heating and electricity systems, capturing synergies and limitations between, e.g., CHP-based DH and fluctuating RE-based productions of heat and electricity.

EnergyPLAN has been applied in a high number of journal articles ranging on different geographies of scale from continents to communities addressing systems ranging from holistic energy scenario designs to the more detailed analyses of particular technologies' behaviour inside energy systems[75].

EnergyPLAN is presented in a higher level of detail in [105].

8.2 Case description and scenario design

The comparison is based on a 2050 100% RE-based energy scenario for Denmark established with and for the Danish Society of Engineers. This scenario is based on wind power, photo voltaics and biomass resources. Heating demands are largely covered by DH from a variety of sources including excess heat from industry, geothermal, heat pumps, CHP, solar thermal and conversion losses from the production of electrofuels [106]. For the analyses in this paper, demands and general supply structure are maintained as explained in detail in [63]; however, technical and economic factors are modified to reflect 3GDH and 4GDH systems, respectively. These modifications are shown in Table 1. A similar methodology has been applied in [10].

	3GDH system	4GDH	Comment
Yearly average supply/return temperatures at DH plant	80°C / 45°C ΔT=35K	55°C / 25°C ΔT=30K	
DH Grid losses	28%	19%	Based on soil temperature of 8°C and average pipe temperatures 2°C lower in forward and 2°C higher in return than the temperatures at the DH plant
DH heat pump COP (resource temp. 5°C; yearly average)	2.9	3.9	Based on a 64% system efficiency, evaporator 5K colder than resource and condenser 5K warmer than

DH heat pump COP (resource temp. 35°C; yearly average)	4.2	7.1	supply temp
Waste heat sources for direct DH application	0.83 TWh +2.28 TWh from district cooling	2.4 TWh +2.28 TWh from district cooling	Fixed element from district cooling
Waste heat sources for indirect DH application through heat pumps	1.67 TWh Added 0.4 TWh to electricity demand	2 TWh Added 0.28 TWh to electricity demand	Electricity demands based on COP with resource temperature 35°C
CHP (Combined cycle)	η_e= 52% & η_t=39%	η_e= 52% & η_t=44%	
DH Biomass boilers with condensation	95%	105%	
Thermal storage	3.17 M€/GWh	3.70 M€/GWh	Based on fixed cost per m^3 and contents proportional to ΔT
Solar thermal	544 €/MWh	382 €/MWh	Based on fixed collector cost per m^2 and increasing efficiency at lower temperatures

Table 1: Modelling assumptions for the comparison between 3GDH and 4GDH

The analyses are based on supplying the same energy demands with the same biomass consumption, with the same ability to balance fluctuating RE electricity sources expressed by the same amount of excess electricity generation and with the same gas exchange with surrounding systems. EnergyPLAN does not have endogenous scenario design optimisation[107]; thus, in order to meet the multiple objectives, iterations are required in which wind power and electrolyser capacities are adjusted to ensure that biomass, gas exchange and critical excess electricity remain the same. With limited onshore options for further wind power deployment in Denmark, only offshore is considered in this iteration.

Regarding costs, the analyses include all energy systems costs, i.a. investment, operation and maintenance and fuel costs for the generation and storage of electricity, heat and electrofuels. In addition, the base scenario also includes costs for energy savings, electric vehicle infrastructure, marginal investment costs for electric vehicles compared to fossil alternatives as well as district heating and electricity grids. For this paper, these additional investment costs as well as operation and maintenance for these are kept constant. All costs are annuitized using a discount rate of 3% and the respective life times of the components.

8.3 Benefits in supply: systems analysis of reduced grid losses and higher efficiencies in production

Table 2 gives an overview of the energy demands of the two scenarios. Transport, industrial demands and final heating demands are constant across the scenarios and only provided for reference. DH supply changes between the scenarios with a reduction of 11% from 3GDH to 4GDH. These reductions are effects of the reduced DH grid losses. Electricity demands are the same – although internal electricity demands in the energy systems (electricity for heating and for electrofuels) change between the scenarios.

	3GDH	4GDH
Electricity demand [TWh]	36.64	36.64
DH supply [TWh]	39.16	34.80

Final individual heating demand [TWh]	14.51	14.51
Transport fuel demand [TWh]	40.23 (Total) 31.13 (Electrofuels) 9.1 (Electricity)	40.23 (Total) 31.13 (Electrofuels) 9.1 (Electricity)
Industrial fuel demands	11.82 (total) 8.41 (Gas) 3.41 (Biomass)	11.82 (total) 8.41 (Gas) 3.41 (Biomass)

Table 2: Electricity, heat and fuel demands. The electricity demand is the sum of exogenously given demands and does not include energy sector internal demands for DH heat pumps, electrolysers or electric boilers.

Compared to 3GDH, 4GDH reduces the need for investments in wind and electrolysers. As shown in Table 3, the need for wind power is reduced by 1500 MW and the need for electrolyser capacity is reduced by 1 GW. The substantial reduction in wind power and electrolyser capacity arises from the scenario design of keeping the use of biomass constant. One could instead choose to use the benefits of 4GDH to reduce the biomass consumption as done in [10].

	3GDH	4GDH
Onshore wind power [MW]	5000	5000
Off-shore Wind power [MW]	14000	12520
PV [MW]	5000	5000
CHP (electric/heat) [MW]	5000 / 3750	5000 / 4231
Electrolyser [MW]	9009	7975

Table 3: System configuration with 3GDH and 4GDH

Total energy systems costs are reduced by approximately 1.5% from 3GDH to 4GDH, but it should be noted that there are large constant elements in the price structure, notably in the transport sector, that directly accounts for over 40% of the total annual costs, diminishing the relative change from 3GDH to 4GDH.

	3GDH	4GDH
Total annual cost [M EUR]	22,373	22,047
Biomass demand [TWh]	52.50	52.51
Critical excess electricity [TWh]	2.47	2.47

Table 4: Aggregated system parameters

As can be seen, the implementation of 4GDH compared to 3GDH results in reduced investment and operation costs equal to an annual cost of 326 MEUR/year - or given the assumptions and uncertainties one should say 300-350 MEUR/year. This energy system saving corresponds to about 10 EUR per MWh of DH produced, excluding building and grid costs. This may be compared to the average DH price for 22 EU countries, which in 2013 was 65.2 EUR/MWh consumed, including taxes but excluding VAT [108].

In addition, the combination of energy savings and 4GDH decreases the primary energy demand and can decrease the reliance on bioenergy while also reducing socio-economic costs [10].

8.4 Assessment of buildings costs

The implementation of 4GDH in buildings involves two challenges: to reduce the return temperature and to reduce the supply temperature.

To reduce the return temperature, improved control of space heating systems and DHW systems must be introduced in existing buildings. For the space heating demand, the least cost solution is expected to be an extra investment in new thermostats with return temperature sensor, which is expected to incur an extra investment cost of 51 EUR per radiator. Though, improved pump control in the form of a pressure difference sensor on critical locations in the building distribution system and the replacement of pumps might be also be needed. With a typical annual heat consumption per radiator of 2.1 MWh and a lifetime of 20 years, it is expected that the yearly space heating costs for enabling the reduction of the return temperature ranges from 0.1 – 1.2 EUR/MWh of space heating demand.

For DHW, it is expected that a new control system is needed for all building types with an estimated cost of 1.7 EUR/MWh DHW. With an assumed distribution between space heating and DHW of 70/30, the annual cost for reducing the return temperature is assumed to be in the range of 0.7 – 1.3 EUR/MWh of end-user consumption. Using the data from the 100% RE-based energy scenario described in Sections 8.2 and 8.3, where the total end-user consumption of DH is 28.2 TWh/year, this cost will total around 19-38 M EUR/year.

While the reduction in return temperature can be made already now in existing buildings, it is expected that lowering the supply temperature to 55°C will only be possible if energy renovations will take place in the scenario over the next 30 years as part of general renovation and energy savings. Likewise, it is expected that the new control system for DHW is sufficient for single-family houses and similar buildings. As such, only the DHW systems in large buildings may need new solutions to reduce the supply temperatures in order to remove legionella from the DHW. Hence, systems removing legionella are expected to be needed in all larger buildings, and it is expected that the investment cost of such a system will be about 8,000 EUR. With an assumed average DHW consumption per legionella removal system of 30 MWh/year and a lifetime of 20 years, this adds a yearly extra cost for larger buildings of 13.4 EUR/MWh of DHW consumption. Using the data from the 100% RE-based energy scenario, and assuming the same distribution between single-family houses and larger buildings in the district heating sector [109], the extra cost for also reducing the supply temperature in the Danish case equals 59 M EUR/year.

In conclusion, the overall costs of a full implementation of 4GDH compared to 3GDH results in a cost range of 78-97 MEUR/year. Since this by nature is an estimate, a reasonable result would be to conclude on a range of 50-100 MEUR/year.

8.5 Assessment of the grid costs

As mentioned in Section 4.1, in general, the capacity requirements to the pipes and to the pumps within DH grids remain unchanged when a reduction in the supply temperature is accompanied by the same reduction in the return temperature. However, in this specific assessment, the temperature differs, i.e. a delta T of 35K in 3GDH and 30K in 4GDH. Therefore, either the investment or the operation costs will be a little higher in the 4GDH alternative.

Here, these costs have been calculated as additional pumping costs in the following way:

- In accordance with Danish District Heating statistics, pumping in average uses approx. 6 kWh electricity in DH plants per MWh of heat supply. A similar figure of 5 kWh_e/MWh_{th} is used in [110]. This figure may of course be lower in the future due to more efficient pumping technologies.
- The electricity demand is approx. proportional to the flow cubed. When assuming the same network, a flow reduction of 16% = (1-30K/35K) will give an electricity reduction of 37% = $(1-(30K/35K)^3)$.
- If assuming 6 kWh_e/MWh_{th} in the 4GDH case, the 3GDH case will thus use about 4 kWh_e/MWh_{th}.

- This equals an electricity demand for pumping of 210 GWh for the 4GDH system (35 TWh DH) and 156 GWh for the 3GDH system (39 TWh DH) equal to a difference of 54 GWh.
- Assuming an electricity production cost of 50-100 EUR/MWh, the additional pumping cost of operating 4GDH is in the order of magnitude of 3-6 MEUR/year.

Since this is a rough estimate, we express the cost difference in the range of 0-10 MEUR/year.

8.6 Comparison of final cost and benefits

Table 5 provides a comparison of the results mentioned above.

Elements of implementing 4GDH instead of 3GDH	Annualized cost
Additional cost within the buildings (investment in equipment)	- 50-100 MEUR/year
Additional cost in the DH grid (operation costs)	- 0-10 MEUR/year
Savings in investments and operation of the DH grid and in the production (system costs) due to lower temperatures.	+ 300-350 MEUR/year
Sum	+ 200-300 MEUR/year

Table 5: Cost assessment of implementing 4GDH instead of 3GDH in a future sustainable energy system in the year 2050 in a country of the size of Denmark.

Costs involve an upgrade of heating systems and the operation of the DH grids, while benefits are lower grid losses, a better utilization of low-temperature heat sources and improved efficiency in the production system (heat pumps, CHP units and boilers). It is quantified how benefits exceed costs by a safe margin with the benefits of systems integration being the most important. Therefore, along with the implementation of future smart energy systems based on RE, there is a large incentive for society, utilities and heat consumers to reduce their temperature demands. In such future systems with low-energy houses, 1 EUR spent in buildings for obtaining lower temperatures will reduce the future supply cost by approx. 4 EUR, giving a net benefit of 3 EUR.

9 Conclusions

This review has addressed the need for a new fourth generation of district heating as a key technology to deliver heat to buildings with low heat demands in future sustainable energy systems. Heat in 4GDH is delivered from non-fossil energy sources at affordable costs and forms an integrated part of overall smart energy systems based on renewable energy including a sustainable use of biomass.

In recent years, international research has provided tangible results that will facilitate full-scale implementation of 4GDH systems as a key component in the transformation into future smart energy systems. An overview of recent scientific publication of papers using or alluding to the 4GDH concept shows a significant increase since 2014. This increase includes papers addressing all the main aspects of 4GDH as previously defined; however, the increase is most notable in connection to 4GDH in Smart Energy Systems and cross-sectoral and renewable energy integration.

Research demonstrates how existing as well as new buildings can be transformed into the 4GDH concept without significant costs. Research also demonstrates how existing and new district heating grids can be converted to operate with 4GDH temperatures also at minor and affordable cost.

While the costs in buildings and grids are minor and affordable, research demonstrates how the benefits to the system are substantial in terms of lower production costs due to lower grid losses and especially higher efficiencies and substantially lower production costs.

The costs and benefits of 4GDH compared to 3GDH have been quantified at a country level assuming the implementation of a sustainable energy system in the future with low-energy buildings. Costs involve an upgrade of heating systems and the operation of district heating grids, while benefits are lower grid losses, a better utilization of low-temperature heat sources and improved efficiency in the production system – heat pumps, CHP units and boilers. It is quantified how benefits exceed costs by a safe margin, with the benefits of systems integration being the most important.

Regarding the implementation, research points to the challenge of establishing a new institutional set-up and shift in paradigm to facilitate the legal framework, ownership and economic incentives needed.

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