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Case Study of a Low-Energy District Heating Network in Energy-Efficient Settlements in Denmark

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Abstract: *The decreased heating demand in low-energy buildings affects the cost-effectiveness of traditionally-designed district heating (DH) systems. This paper presents the innovative low-energy DH concept, which is based on low-temperature operation. The annual energy performance of a low-energy network for low-energy houses in Denmark was investigated. We considered the influence of the human behavior on the energy demand, the importance of the degree of buildings connected to the network and a socio-economical comparison with ground source heat pumps. In the North European climate, the human behavior can lead to 50% higher heating demand and 60% higher heating power than expected according to reference values in standardized calculation of energy demand pattern in energy-efficient buildings. Next, we proved that low-energy DH systems are robust systems that ensure the security of supply to each customer in a cost-effective and environmentally friendly way in areas with linear heat density down to 0.20 MWh/(m·year). This suggests that the mandatory connection of low-energy buildings to DH in specific areas, by means of detailed energy planning, would improve the energy efficiency and the overall socio-economy and it is strategic for effective energy policy. The levelised cost of energy in case of low-energy DH supply is competitive with the scenario based on ground source heat pumps. The investment costs represent up to three quarters of the overall expenditure, over a time horizon of 30 years; hence, the implementation of an energy system that fully relies on renewable energy needs substantial capital investment, which in the long-term period is sustainable, from the environment and socio-economical point of views. The low-energy district heating concept fits the vision of the future energy sustainable society.*

Keywords: *district heating, low-energy buildings, low temperature, human behavior.*

1. INTRODUCTION

1.1. The low-energy concept applied to district heating

District Heating (DH) covers 60% of the heating demand in Denmark and has a large influence on the rest of the energy system. DH plays a central role in the future Danish energy system based on Renewable Energy (RE) [1]. Hence many communities have prepared plans for implementing the vision of a society that achieves drastic energy savings and fully relies on RE [2]. The possibility of satisfying the energy demand in communities with DH is high not only in cold climate countries, but also in other countries [3], [4], so that the potential is huge. Nevertheless, the cost-efficiency of DH supply to low-energy buildings may be critical, especially due to the fixed costs that derive from capital intensive investments. Furthermore, it is not mandatory in case of low-energy buildings to connect to DH, according to the Danish Building Regulation. Finally, traditionally-designed networks would often have sub-optimal energy performance, because of over-dimensioned design and unnecessary high operational temperatures. The application of the low-energy concept to the DH technology aims at three main targets. The first one is to guarantee comfort, with regards to delivery of Domestic Hot Water (DHW) and to Space Heating (SH) requirements, by exploiting low-grade energy sources and RE. The second objective is to match the exergy demand of such applications with the exergy available in the supply system, by making the temperature levels of the supply and the demand closer. Finally, it aims at reducing the heat loss in the distribution network. The main design concepts are: 1) low-size media pipes. This is achieved by allowing a high pressure gradient in the branch pipes connected to the unit with instantaneous DHW preparation or by installing units with storage of DH water. The latter one consists on a heat exchanger coupled to a water storage tank on the primary side, which ensures low continuous water flow and thus low-size media pipes in house connections. 2) Low temperatures: 50-55°C in the supply line and 20-25°C in the return line. The technical and economical feasibility of such systems were investigated from the theoretical point of view in [5] and applied in [6]. Lowering the supply and return temperatures increases the final energy efficiency of the systems and decreases the heat losses [7]. 3) Twin plastic pipes instead of single steel pipes. This leads both to lower investment costs for the civil works connected to the laying of the pipelines and to lower distribution heat losses. The investigation proposed in this paper aims at developing a proposal on how to best apply the low-energy DH concept for low-energy buildings. We evaluated the annual energy performance and the socio-economy of a demonstrative network, based on realistic energy loads that derived from a model of the human behavior. Next, we discussed the economically-reasonable lower limit for the heat demand density for which the connection to low-energy DH networks is cost-effective and energy efficient.

2. METHODS

2.1. Simulation of the energy use in low-energy buildings

Dynamic energy simulations were carried out with the software IDA-ICE [8]. A special module, developed in [9], evaluated the realistic human behavior and its effects to the energy use. The model is based on measurements in 10 apartments and 5 single family houses; the following factors were measured every 10 minutes for an 8-month period: indoor environment factors (operative temperature, relative humidity, CO_2 concentration), outdoor environmental factors (air temperature, relative humidity, wind speed, solar radiation), human behavior (window state open/closed, opening angle, temperature set-point of the thermostatic valves in radiators). These factors were used to create a standardized human behavior model for energy simulations in IDA-ICE; the model takes into account the window opening behavior and the heating set point. A linear regression was used to calculate the relationship between the heating set point and environmental factors. Moreover, a realistic occupancy schedule was made by adopting the model in [10]. Finally, we determined the expected energy use and peak loads in two typical types of low-energy buildings "class 1"and "class 2015" according to the Danish Building Code [11]: a row house, whose floor area is 114 m^2 and a detached, single-family house, whose floor area is 196 m^2. A complete description of the two reference houses is available in [12].

Table 1 Main input data for the energy calculations in the reference houses.

House type	Case	Internal gains [W]			Ventilation [L/(s·m²)]	Heating set point [°C]
		Occupants	Lighting	Equipment		
Row house	Be06	170	400 (lighting + equipment)		0.45 (CAV)	20
	1	2 persons, always	300	100	0.45 (CAV)	20
	2	2 persons, always	schedule**	schedule**	0.45 (CAV)	20
	3	3 persons , schedule*	schedule**	schedule**	0.45 (CAV)	20
	4	3 persons, schedule*	schedule**	schedule**	0.07-0.7 (VAV)	20
	5	Occupancy model	schedule**	schedule**	0.45 (CAV)	Human behavior
Detached house	Be06	294	686 (lighting + equipment)		-	20
	1	294	schedule***	schedule***	-	20
	2	2 persons, always	schedule***	schedule***	-	20
	5	3 persons , schedule*	schedule***	schedule***	-	Human behavior

* Weekdays 17:00-8:00: 3 people; 15:00-17:00 (1.5 persons). Weekends: 3 people. ** Lighting: 685 W, equipment: 240 W; schedule: 6:00-8:00 and 15:00-23:00. *** Lighting: 1165 W, equipment: 475 W; schedule: 6:00-8:00 and 15:00-23:00.

We consider 5 different cases for the reference row house and three cases for the reference detached house. The cases were chosen with the aim of comparing the influence of the human behavior on energy use to the effect of various system control strategies and environmental parameters. The cases are: 1) the input data are similar to what is required by the software Be06 [13]. Be06 is the Danish official software for energy certification of low-energy buildings. 2) The lighting and equipment are set with a schedule. The total electrical energy use in case 2 is equal to case 1, but the constant loads are replaced by variable loads. 3) The lighting, equipment and human occupancy are set with a schedule; the constant loads are replaced with variable loads. 4) Same as case 3; a Variable Air Volume (VAV) ventilation system replaces the Constant Air Volume (CAV) ventilation system. 5) The human behavior and occupancy models are introduced.

2.2. Performance of the low-energy DH network

In order to investigate the dynamic energy performance of low-energy DH networks for low-energy buildings, an existing network layout was adapted from [14]. In the simulations the consumer units consist of substations equipped with a heat exchanger for instantaneous preparation of DHW and without energy storage; they have a nominal power of 32 kW and they require a minimum pressure difference of 0.3 bar. In order to ensure a reasonable waiting time for DHW outside the heating season, the design thermal bypass temperature was set to 40°C in each consumer. Pipes with nominal diameter smaller or equal to 32 mm are Aluflex twin pipe type, while for bigger sizes steel twin pipes were chosen, see Table 2.

Table 2 Pipe types and length of the pipeline. Alx: Aluflex twin pipe. Tws: steel twin pipe.

	Length [m]							
	Alx 20	**Alx 26**	**Alx 32**	**Tws 32**	**Tws 40**	**Tws 50**	**Tws 65**	**Total**
Row houses	239.1	112	240.6	88.5	33.8	7.7	100.7	823.4
Detached houses	315.7	150.1	555.5	149.7	80.7	7.7	100.7	1360.1

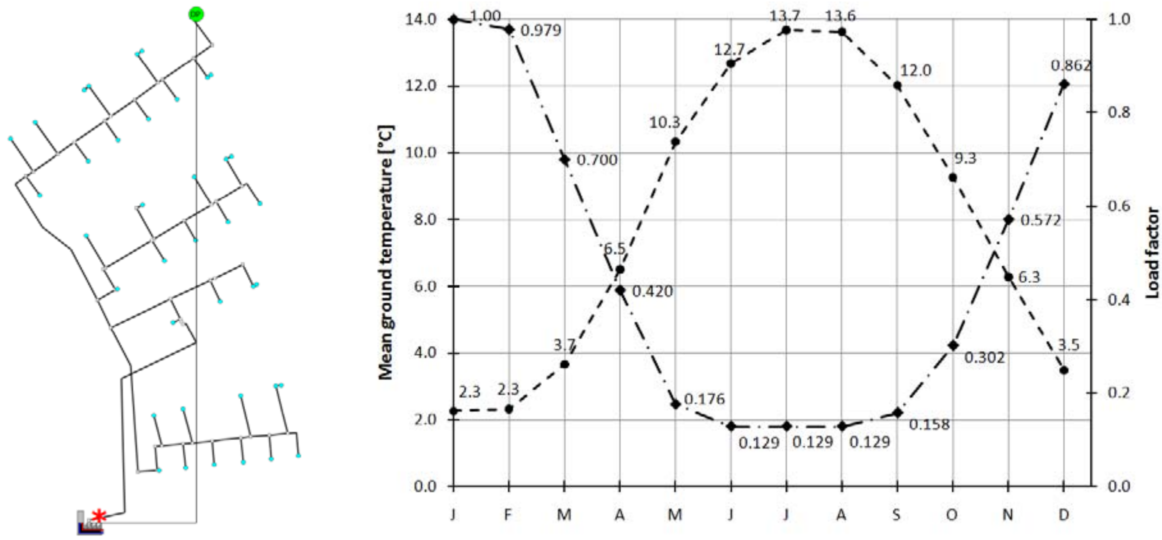

Fig. 1 Network layout in the case of row houses (left). Mean monthly ground temperature in Denmark (source: [7]) and heat load factor for the case with row houses and standard energy use (right).

In the cases of detached houses, the distance between the nodes representing the consumers was multiplied by a factor 3. For each case an annual simulation was made. The main input values consisted of the geometric and thermal parameters of the pipelines, the ratio between the average energy demand for a specific month and its maximum yearly value (load factors), the number of hours for each month and the mean monthly ground temperature. The results from such simulations were compared to dynamic simulations with detailed 24-hour load profile for a typical day during the heating season and for a typical day in summer, in order to evaluate the accuracy of the annual simulations with averaged monthly energy use. Fig. 2 shows the hourly values of the load factor for the case with row houses and standard energy use. We consider a typical summer day during which heat is supplied only for the DHW preparation and the typical average day in January (SH + DHW). The load profile of the average day in a month is defined by the average hourly values of energy use, calculated as:

$$LF_i = \left(\frac{\sum_{j=1}^{n} E_{i,j}}{\left(\sum_{j=1}^{n} E_{i,j}\right)_{max}} \right) \quad (1)$$

where LF_i is the load factor for a specific hour i, $E_{i,j}$ is the energy use in the hour i of the day j and n is the number of days in the month considered. Finally, we compared the energy performance of the low-energy DH network to other reference examples of DH networks in low heat demand areas.

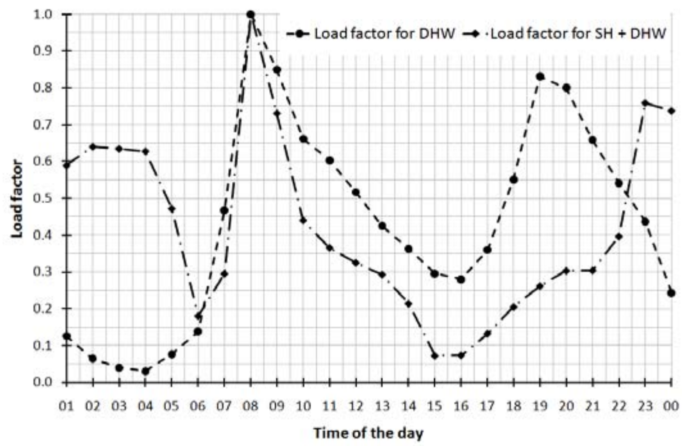

Fig. 2 Row houses and standard energy use. Load factors in a summer day (DHW only) and for the average day in January (SH + DHW). The peak values for the hourly energy use are 0.50 kWh and 2.45 kWh, respectively for DHW only and SH + DHW.

2.3. Degree of connected users

During the feasibility study of a DH network in a low heat demand density area, an economical investigation of a minimal feasible degree of connected consumers to the network must be made, since there is not mandatory connection for low-energy buildings, even in zones that were planned to be supplied by DH or with an already existing network. Simulations were performed to investigate the performance of the low-energy DH network depending on the different percentage (from 100% down to 10%) of low-energy buildings connected. We kept the last consumer of each street connected, so that the total network length did not vary from case to case. Next, the cost analysis shows the minimal cost-effective degree of connection, which can be generalize in terms of linear heat density. The linear heat density is defined as the ratio between the heat production and the trench length of the network.

2.4. Socio-economy

As final step we carried out a simplified socio-economic evaluation based on cost figures from reference reports [15], [16]. The cost comparison refers to the cost of 1 kWh, when buildings are supplied with either DH or with individual Ground Source Heat Pumps (GSHP). The interest rate of 6% and a period of 30 years were considered; this is in line with what the Danish Ministry of Finance requires for public investment analyses. However, other long-term analyses suggest that a discount rate as low as 3% is reasonable [17]. The significance of the discount rate is not to be underestimated particularly in cases that foresee a shift between operational costs to investment costs, such the ones considered in this article. It is important to underline that lower discount rates would improve the overall economy of the DH systems considered in this paper, and therefore the economic results are on the safe side.

3. RESULTS AND DISCUSSION

3.1. Energy use in low-energy buildings

The results from the energy simulations of the two reference houses indicate the same tendency, when considering the heating demand. First, the heating demand increases by a factor 2 in comparison to standard calculations, when the human behavior is taken into account. Moreover, the human behavior significantly affects the magnitude of the heating peak load: +27% for the single family house and up to +60% for the row house, with standard simulation as reference. Next, the heating demand increases of around 5%, when internal gains are variable over the time. Finally, for the DH network operation point of view, it is interesting to underline that the duration of the heating season is approximately one month shorter in low-energy buildings than in standard buildings, considering the North European climate.

Table 3 Energy use in the reference houses for the different cases.

Type of house	Case	Primary energy demand* [kWh/(m²·year)]					
		Lighting	**Equipment**	**Other el.**	**SH**	**DHW**	**Total**
Row house	**Be06**	-	-	**4.7**	**18.8**	**12.8**	-
	1	54.3	19.3	**4.3**	**17.1**	**13.1**	108.0
	2	54.3	19.3	**4.3**	**18.0**	**13.1**	108.9
	3	54.3	19.3	**4.3**	**17.1**	**13.1**	108.0
	4	54.3	19.3	**2.0**	**11.7**	**13.1**	100.3
	5	54.3	19.3	**4.3**	**35.0**	**13.1**	125.9
Detached House	**Be06**	-	-	**2.4**	**15.4**	**12.3**	-
	1	54.3	22.3	**2.4**	**17.2**	**11.6**	107.7
	2	54.3	22.3	**2.4**	**18.1**	**11.6**	108.6
	5	54.3	22.3	**2.4**	**31.8**	**11.6**	122.3

*Primary energy factor for electricity = 2.5; primary energy factor for heat = 0.8.

3.2. Low-energy DH network: annual energy figures

We performed the energy performance analysis of the DH network for row houses and of the DH network for detached houses. We considered only the simulation case 1, where the energy demand is calculated according only to building physics parameters, and the simulation case 5, where the human behavior is taken into account. The heat production, the heat loss and the ratio between distribution heat loss/heat production for each month of the year are shown in Fig. 3. The energy performance drastically improves, in comparison to medium-high temperature DH networks (T_{supply}>=80°C) applied to low-heat density areas. The low-energy DH concept is technically a good solution both for row houses and for detached single family houses, having a share of heat loss, in a yearly base, between 14% and 20% of the total heat production. The ratio between the heat loss and the year-round heat production decreases typically from 20%, in case of standard energy calculations, to 14%, if the human behavior is taken into account.

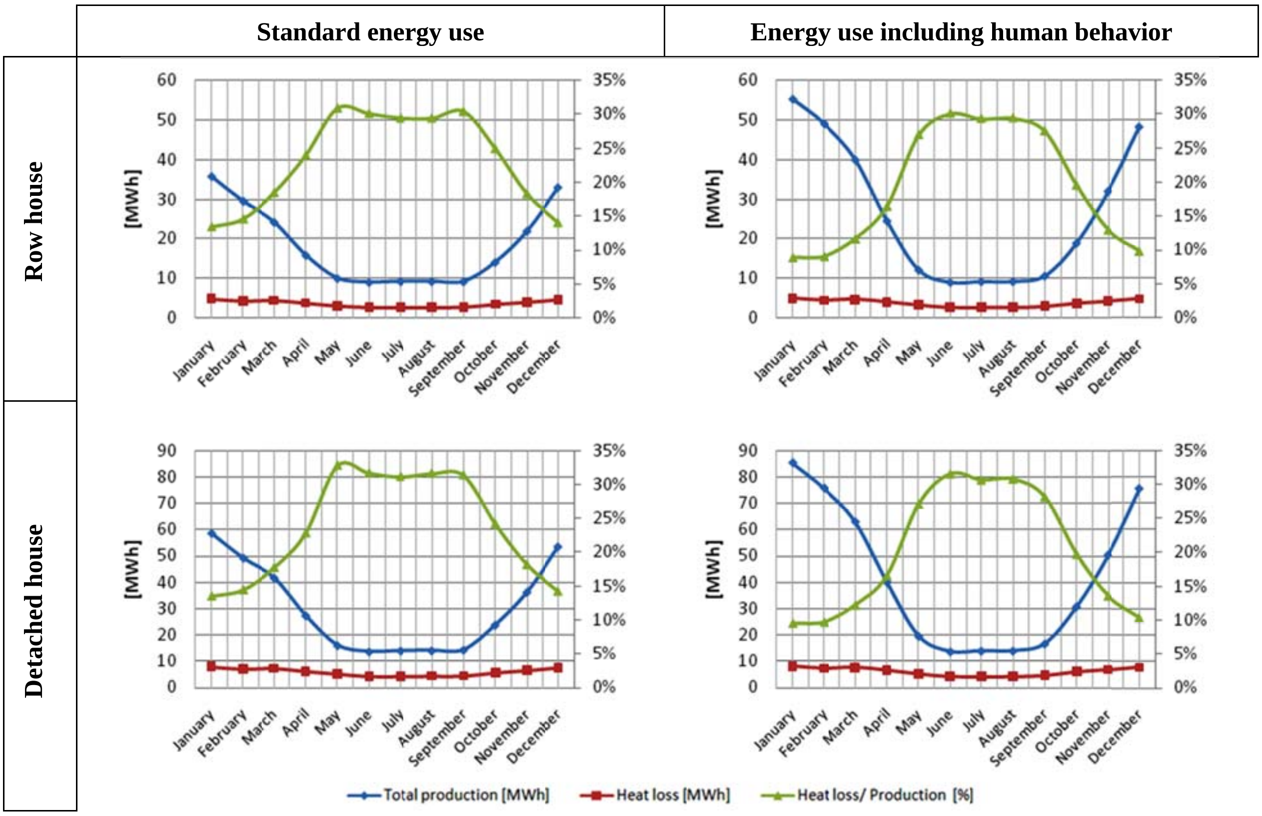

Fig. 3 Monthly heat production and heat loss [MWh] and distribution heat loss/produced heat ratio. Case with row houses (up); case with detached houses (down). Standard energy use (left); energy use including human behavior (right).

Table 4 Comparison between network energy simulation with average monthly values and hourly values; January and July.

Simulation	Type of buildings	Case	Total heat production [MWh]		Heat loss[MWh]	
			January	*July*	*January*	*July*
Hourly [MWh]	Row houses	1	35.21	9.13	4.68	2.87
		5	58.25	9.13	4.91	2.87
	Detached houses	1	58.26	14.25	7.73	4.74
		5	87.31	14.25	8.10	4.74
Annual [MWh]	Row houses	1	35.76	9.20	4.81	2.71
		5	57.40	9.23	4.93	2.71
	Detached houses	1	58.58	14.06	7.93	4.38
		5	85.29	14.02	8.12	4.31
Difference [%]	Row houses	1	1.6	0.7	2.8	-5.6
		5	-1.5	1.1	0.4	-5.6
	Detached houses	1	0.5	1.3	2.5	-7.7
		5	-2.3	-1.6	0.2	-9.2

On one hand that demonstrates that the human behavior has a great impact on the energy efficiency of the network; on the other hand, it confirms that the energy saving policies in the building sector cannot rely only on technological aspects, but need to address the participation of the end-users. Moreover, the network design is robust and is capable to handle heat loads greater than the design values, without any hydraulic issues and assuring the security of the heat supply. Such situation occurs, for instance, when going from heat demand purely based on the building material physics and standard indoor environment conditions in energy-efficient buildings, to heat demand calculations that take into account users' misbehavior. This must not lead to underestimate the importance of energy savings, since they represent the prerequisite for implementing the vision of a fossil-fuel-free energy sector. The conclusion is that the society can achieve the full potential of energy conservation measures in the building sector and their integration with an efficient energy supply system only with the decisive involvement of the final users. We discuss now the accuracy of the simulations. The annual simulation with average monthly input values gives sufficient accuracy in comparison to the 24-hour dynamic simulations of the typical day of that specific month, as it possible to see in Table 4. Nevertheless, it is important to underline that the accuracy in the calculation of the network energy performance in long periods without SH (summer season) is more sensitive than during the heating season. The variation can be up to 9%, in case of calculation of heat losses. This is due to the simplification introduced when considering average monthly load values, which lead to smoother load profile than in case of calculation with hourly load values.

3.3. Low-energy DH network: energy performance versus linear heat density

Considering the whole DH sector in Denmark, the ratio between the distribution heat loss and the produced heat is 16% and the value rises up to 21%, if the networks serving the 3 biggest metropolitan areas are not included.

Fig. **4** shows the ratio between distribution heat loss and total produced heat versus the linear heat density, for the case-studies. Each point in the graph represents a case with a specific linear heat density, which corresponds to a specific number of buildings connected to the network, the maximum number of building connected being 40. The different values of linear heat density are set by disconnecting 10% of the dwellings in each step from the original network with 40 houses. The procedure was repeated with 10 different disconnection patterns, from purely randomized to more uniform ones. The values of the heat loss/produced heat ratio lay between the curve showing the case with row houses and energy use including human behavior and the curve of detached houses and standard energy use. The distribution heat loss in the low-energy DH network are lower than 20% of the heat produced, if the line heat density is higher than 0.25 MWh/(m·year). This demonstrates that it is possible to integrate low-energy buildings in the existing Danish DH networks without decreasing the energy performance of the whole DH system. The results not only confirm, but even go over the statement made in [16], where the authors claimed that areas with a linear heat density of 0.30 MWh/(m·year) can be supplied by DH in a cost-efficient way. The low-energy DH concept is strategic for reaching ambitious energy and climate targets and has the potential for being widely implemented in Europe, taking into account what concluded in [18] about the European heat market: the demand of heat dominates the demand side in the European energy system and almost the same specific heat demands appear in Western, Central, Eastern, and Northern Europe. Similar conclusion can be drawn for other extra-

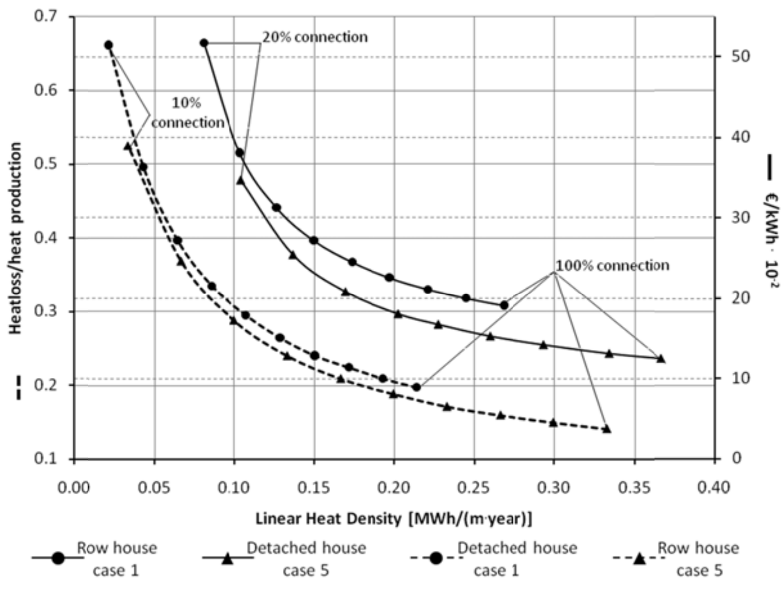

Fig. 4 Heat loss/total produced heat vs. the linear heat density (- - -). Specific energy cost (—). The picture shows the bottom and top curves. All the values lies between the top and bottom lines, for all the cases considered.

European countries where energy saving measures and efficiency in the energy supply agenda are priorities in the political agenda. The curves reporting the cost of the energy unit show that in case of houses with the lowest total heat demand (dense, row houses, standard energy use) the specific energy cost is the highest, while the specific energy cost is the lowest in case of houses with the highest total heating demand (detached, single-family houses). Nevertheless, the overall expenditure for heating purposes strictly depends on the actual total energy use, and it is therefore highest for the detached, single-family houses than for the dense, row houses.

3.4. Socio-economy

The levelised cost of energy in case of low-energy DH supply is competitive with the GSHP-based scenario, which is considered among the best alternative solution for efficiently heating in low-heat demand density areas. The cost of heat for the end-user is 13.9-19.3 c€/kWh (excl. VAT, referred to 2010), respectively for the case with the low-energy “class 2015” detached houses and the users in the low-energy “class 2015” row houses. In 2010, in the capital region of Denmark the heat price was ~6.9 c€/kWh (excl. VAT); that means that the specific heat price for the final consumer in the low-energy area would be 2-3 times higher than the current price. Nevertheless, the overall expenditure could be very well similar to the current bill, thanks to drastic energy savings that offset the effect of higher energy prices. A 30-year time horizon, 6% interest rate, energy use as expected from standard calculations and current energy prices for heat and electricity purchase for DH companies in Denmark were considered. In the future energy systems based on RE it is expected that the operational costs, i.e. neglecting the investment costs, will increase due to higher prices for RE energy purchasing. On the other hand, this is not critical for two reasons, the first being that the price for business as usual, fossil-fuel-based heat will increase as well, and the second one being that the share of the operational cost in the overall energy cost is not the most critical, above all in energy-efficient areas; in fact the energy costs for DH energy supply count for 18-28% of the total costs, while the investment costs represent 63-72% of the overall expenditure. Similar conclusion can be drawn for the case of HP heat supply, as the energy-related cost has a share of 12-19%. The implementation of an energy system that fully relies on RE needs substantial capital investment, which in the long-term period is sustainable, from the environment and socio-economical point of views. The costs of such a scenario are at a comparable level with the current situation or even more profitable, if the environmental costs of keeping business as usual practice, fuel savings and health issues are taken into accounts. We can conclude that the low-energy DH concept fits the vision of the future energy sustainable society, as expressed in [19].

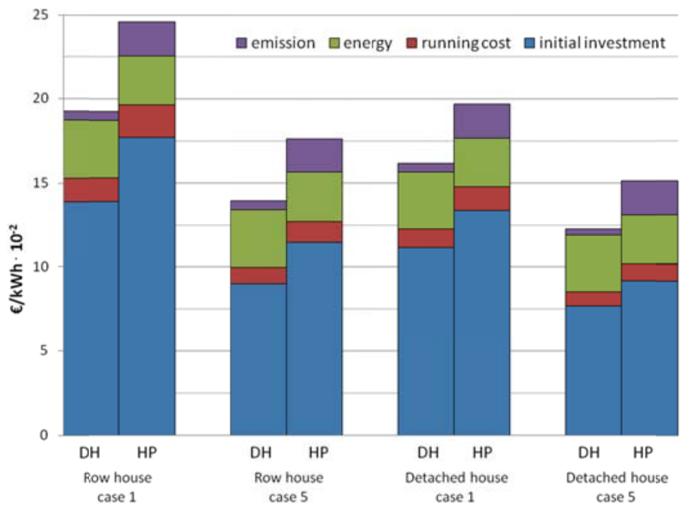

Fig. 5 Comparison of the levelised cost of energy in case of heat supply based, respectively, on low-energy DH and individual heat pumps.

4. CONCLUSIONS

In this paragraph we gather the main findings of this paper and guidelines that can be followed to improve the energy efficiency and the exploitation of RE in the heating sector. First, the human behavior can lead to 50% higher heating demand and 60% higher peak loads than expected according to reference values in standardized calculation of energy demand pattern in energy-efficient buildings. Since energy savings represent the prerequisite for implementing the vision of a fossil-fuel-free energy sector, the conclusion is that the society can achieve the full potential of energy conservation measures in the building sector and their integration with an efficient energy supply system only with the decisive involvement of the end-users. The cases considered, although they refer to the Danish tradition in the construction sector and to the Danish climate, have a general value and are adaptable to other situations. The human behavior is the factor that affects the most the energy use in low-energy buildings and should be included in energy simulations. Next, we proved that low-energy DH systems are promising solutions, when assessing cost-effective and reliable solution for supplying the heating demand in energy-efficient areas. The linear heat density can be used as a representative value for feasibility studies of DH. Low-energy DH networks are capable of supplying heat in a cost-effective and environmentally friendly way in areas with linear heat density down to 0.20 MWh/(m·year). Such systems are robust and ensure the security of supply to each customer, even in case of energy use patterns that differ from the expectations. The low-energy DH concept is strategic for reaching ambitious energy and climate targets and has the potential for being widely implemented in all the countries where energy saving measures and efficiency in the energy supply system are priorities in the political agenda. This suggests that the mandatory connection of low-energy buildings to DH in specific areas, by means of detailed energy planning (as in Denmark in the 1970s) would improve the potential for energy efficiency and it is strategic for effective energy policy. The levelised cost of energy in case of low-energy DH supply is competitive with the GSHP-based scenario, which is considered among the best alternative solution for efficiently heating in low heat demand density areas. The cost of heat for the end-user would be 13.9-19.3 c€/kWh (excl. VAT), respectively for the case with low-energy "class 2015" detached houses and the case with low-energy "class 2015" row houses. This is ~20% lower than the correspondent energy unit cost for the GSHP case. The energy costs for DH energy supply count for 18-28% of the total costs, while the investment costs represent 63-72% of the overall expenditure. Similar conclusion can be drawn for the case of HP heat supply, as the energy-related cost has a share of 12-19%. The implementation of an energy system that fully relies on RE needs substantial capital investment, which in the long-term period is sustainable, from the environment and socio-economical point of views. The costs of such a scenario are at a comparable level with the current situation or even more profitable, if the environmental costs of keeping business as usual practice, opportunities of fuel savings and health issues are taken into accounts. The low-energy DH concept fits the vision of the future energy sustainable society.

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