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Integration of Building energy and energy supply simulations for low-energy district heating supply to energy-efficient buildings

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ABSTRACT

The future will demand implementation of $C0_2$ neutral communities, the consequences being a far more complex design of the whole energy system, since the future energy infrastructures will be dynamic and climate responsive systems. Software able to work with such level of complexity is at present a missing link in the development. In this paper is demonstrated how a link between a dynamic Building Simulation Programme (BSP) and a simulation program for District Heating (DH) networks can give important information during the design phase. By using a BSP it is possible to analyze the influence of the human behaviour regarding the building and link the results to the simulation program for DH networks. The results show that human behaviour can lead to 50% higher heating demand and 60% higher peak loads than expected according to reference values in standardized calculation of energy demand. The analysis also shows that the connection of low-energy buildings to DH networks is potentially a good solution in Denmark for reaching the climatic goals, but a high degree of connection must be reached, especially for detached houses, where most of the buildings in a typical community must be connected to ensure a reasonable economy..

1. Introduction

According to the EU energy policy, new buildings must be nearly-zero-energy buildings and deep energy conservation measures shall be applied in existing buildings. To reach such targets, it is necessary that buildings are operated with the optimal degree of energy efficiency, by introducing measures such as thermal insulation, energy efficient windows, and heat recovery. Moreover it is fundamental to integrate passive and active energy measures, possibilities of energy storage and of Renewable Energy (RE) exchange. The final target is finding the most cost-effective ways of coupling energy conservation policies with the development of energy smart grids, which can assure the implementation of $C0_2$ neutral communities. In order to cope with this challenge it is necessary to handle with the fact that both low-energy buildings and future energy infrastructures are dynamic and climate responsive systems. Software able to work with such level of complexity is a missing link in the development. In this paper a link between a dynamic BSP and a simulation program for DH networks is shown.

In Denmark 62% of the heating demand is covered by DH which plays a strategic role in integrating multi-sources of RE-based heat into the energy supply system. DH plays a central role in the future Danish energy system based on RE (Lund et al 2009) and has a large influence on the rest of the energy system (Möller et al 2010), (Østergaard 2003). As a consequence of this have many communities made plans for preparing the energy system to implement the vision of a society that achieves drastic energy savings and fully relies on RE (Østergaard 2011).

A DH network can integrate, for instance, large scale heat pumps, solar thermal energy plants and also waste heat – this being a good environmental solution since more than 90% of waste in Denmark is incinerated and most of it is used for DH and electricity production (Kristjansson 2008). The option of fulfilling the energy demand in communities with district energy is possible not only in cold climate countries, but also in other countries (Lund 2007), (Lund 2010),

However, in relation to low energy buildings there are several challenges for traditional DH. Heat losses from distribution network are relatively high comparing to the energy used. The income from the consumed energy is small while operational and maintenance costs (including metering, administration costs) remain the same. Also, investment costs are very high in relation to the income from the supplied energy and it can take long time to pay them back. Another challenge is that according to the Danish Building Regulation in the case of low energy buildings, it is not mandatory at present time to connect to DH. Finally, traditionally-designed networks would often have sub-optimal energy performance, because of over-dimensioned design and unnecessary high operational temperatures.

The quality of the energy – the exergy – is a key issue, when evaluating energy efficiency and energy savings of systems. Electricity and mechanical energies are expensive high quality energies, as opposed to low-temperature level water required for heating. Since low-temperature DH network delivers low-temperature water, RE can be integrated easily. There are three main targets for the concept of low-energy DH technology:

1. Guarantee comfort and delivery of Domestic Hot Water (DHW).
2. Match the exergy demand with the exergy available in the supply system, by making the temperature levels of the supply and the demand closer to each other.
3. Reducing the heat loss in the distribution network.

The main design concepts are:

1. Small-size media pipes – 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.
2. Low operating temperatures: down to 50-55°C in the supply line and 20-25°C in the return line.
3. Twin plastic pipes are used rather than single steel pipes, whenever is possible.

1.1 Problem statement

Building design must evolve from today's practice – where the individual building parts are optimized separately – into a future where the whole building, including all installed systems, is optimized by integrating innovative technologies that will furthermore make the building itself an active part of the total energy system. Integrated design is a design process informed by multidisciplinary knowledge, where different software plays an important role in the designing process. Numerous simulation programs from different kinds of engineering fields (indoor climate, energy balance, DH, life cycle assessment etc.) exist today, but their capabilities are not used in an integrated way and optimization opportunities are often lost.

The purpose of this paper is to demonstrate the importance of handling links between different simulation tools in order to manage the implementation of $C0_2$ neutral communities. In this paper the link between a dynamic energy simulation program for buildings and a simulation program for DH networks is demonstrated. The results of the investigation give an example of how to analyze a community and make recommendations for applying the low-energy DH concept for low-energy buildings. The annual energy performance is evaluated as well as the socio-economy of a demonstrative network based on realistic energy loads that derived from a human behaviour model. Finally this paper comments on the reasonable lower limit for the heat demand density for which the connection to low-energy DH networks is cost-effective and energy efficient.

2. Methodology of investigation

2.1 Simulations of energy use in low energy buildings

The energy demand is influenced by the user behaviour, which should be therefore taken into account in energy calculations. Unfortunately, there is no such practice. Experience shows that there is a big difference between the calculated energy use and the actual facts in real life – that is the consumers having a higher temperature indoors than the reference values in the Building Regulations. This means that the energy use calculated accordingly to the Building Regulation in many cases is it the smallest obtainable, one.

Since it is very important to evaluate realistic human behaviour and its effects on the energy use in order to get realistic results a BSP, which can handle this challenge has been chosen in this investigation. At the Technical University of Denmark, Civil Engineering there has been developed a human behaviour model as a part of a Ph.D. project (Andersen 2009) linked to the BSP software IDA Indoor Climate and Energy 4 (IDA-ICE Version 4) (EQUA 2011). IDA ICE is a simulation tool, which use a whole-year detailed and dynamic multi-zone simulation application for the study of thermal indoor climate as well as the energy use of the entire building.

IDA ICE has been programmed in the simulation languages Neutral Model Format and Modelica using symbolic equations. This makes it possible for the advanced user to write individual mathematical model of a system, which need to be adapted to a specific advanced problem. The modular nature of IDA-ICE makes it possible to write individual models extending its capabilities as needed by the individual user (Crawley et al. 2008) (EQUA 2011). In this paper the focus has been on using the individual model for realistic human behaviour created by Andersen (2009).

The model was based on measurements every ten minutes for an eight month period in 15 dwellings (10 apartments and 5 detached houses) of the most important parameters: indoor environment parameters (operative temperature, relative humidity, CO_2 concentration), outdoor environmental parameters (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 parameters were used to create a standardized human behaviour model for energy simulations in IDA-ICE; where the model include window opening and the heating set point. A linear regression was used to calculate the relationship between the heating set point and environmental factors. Based on this, a realistic occupancy schedule was made by Andersen (2009) by adopting a model of Richardson et al. (2008) based on 6500 measurements in households in the UK.

Studies have shown that the energy use can vary up to 3 times (Andersen 2009) when comparing among individuals. Peoples´ misuse of energy leads to higher energy use thus it is most important to make the consumers understand how to save energy. User behaviour can be improved by information, advice, full consideration to house design and tariffs.

2.1.1 Reference low energy buildings

In order to investigate the influence of individual human behaviour on actual buildings two common housing types in Denmark has been selected as reference for low energy buildings:

- A terraced house (light weight construction) in Ullerødbyen in Hillerød 114 m^2 (ONV Architects maa|par 2008).
- A detached single family house (heavy weight construction), made by type house producer Eurodan Huse A/S, 196 m^2 (Rose J. 2007).

The individual human behaviour has been analyzed by setting up five different cases for the terraced house and three for the detached house. The cases were chosen in order to compare the influence of the human on energy use to the effect of various system control strategies and environmental parameters. All the cases are with ventilation system constant air volume (CAV), except no. 4 which is replaced by a variable air volume (VAV):

1. Case with parameters close as possible to the initial data from Be06 (SBi 2006) (constant internal gains).

Be06 is the Danish official software for energy certification of low-energy buildings.

2. Case with scheduled lighting and equipment (in order to see the influence of variable internal gains on the energy use). The total electrical energy use in case 2 is the same as in case 1.
3. Case with scheduled lighting, equipment and scheduled occupancy (in order to see the influence of variable occupancy on the energy use).
4. Same as case 3 with the ventilation system replaced by a variable air volume (VAV).
5. The human behaviour and occupancy models are introduced.

For the detached single family house cases 1, 2 and 5 were made. For both building types they were simulated as one zone due to the complicity of human behaviour model.

The expected energy use and peak loads for the terraced house and detached house are according to low energy buildings class 1 in the Danish Building Regulation (2008).

The parameters that are different between the cases are listed in Table 1.

Table 1. Main input parameters for different cases in IDA ICE for terraced houses and detached houses.

Case	Internal gain [W]			Venti-lation [L/(s·m^2)]	Heating set point [ºC]
	Occu-pants	Light-ting	Equip-ment		
Terraced house					
Be06	170	400		0,45 (CAV)	20
1	2 pers. always	300	100	0,45 (CAV)	20
2	2 pers. always	sche.**	sche.**	0,45 (CAV)	20
3	3 pers. sche.*	sche.**	sche.**	0,45 (CAV)	20
4	3 pers. sche.*	sche.**	sche.**	0,07-0,7 (VAV)	20
5	Occu-pancy model	sche.**	sche.**	0,45 (CAV)	Human behaviour
Detached house					
Be06	294	686		/	20
1	294	sche.***	sche.***	/	20
2	2 pers. always	sche.***	sche.***	/	20
5	3 pers. sche.*	sche.***	sche.***	/	Human behaviour

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

2.2 Performance of low-energy district heating network with low energy buildings

In order to investigate the dynamic energy performance of low-energy DH networks for low-energy buildings, an existing low-energy DH network model was adapted (COWI 2009) using the TERMIS Version 2.10 software (TERMIS 2010). The length of the network is 823 m for the terraced houses and 1360 m for the detached houses. In the original network there are 29 Heat Exchangers (HEs) and 11 heat storage units. In the simulations only HE units were considered for all consumers and a total of 40 identical buildings were supplied by the DH network. The consumer units in the simulations consist of substations equipped with a HE 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. The design thermal bypass temperature was set to 40°C in each consumer, in order to ensure a reasonable waiting time for DHW outside the heating season. Pipes with nominal diameter smaller or equal to 32 mm are aluflex twin pipe type, while for bigger sizes steel twin pipes were chosen.

Four cases from IDA-ICE energy simulations were chosen to be implemented in TERMIS:

1. 40 terraced house, Standard energy use (case 2).
2. 40 terraced house, Energy use including human behaviour (case 5).
3. 40 detached house, Standard energy use (case 2).
4. 40 detached house, Energy use including human behaviour (case 5).

In the cases of detached houses (case 3 and 4), pipe distance between consumers was multiplied by factor of 3. For each case an annual simulation was made.

The key input values for TERMIS consisted of the building heat demand profiles (output of the previous simulations in IDA-ICE), the geometric and thermal parameters of the pipelines, the ratio between the average energy demand for a specific month and its maximum annual value (load factors), the number of hours for each month, and the mean monthly ground temperature. Fig. 1 shows an example of the input data representing the mean monthly ground temperature in the surroundings of the pipes and the load factors for the annual simulations.

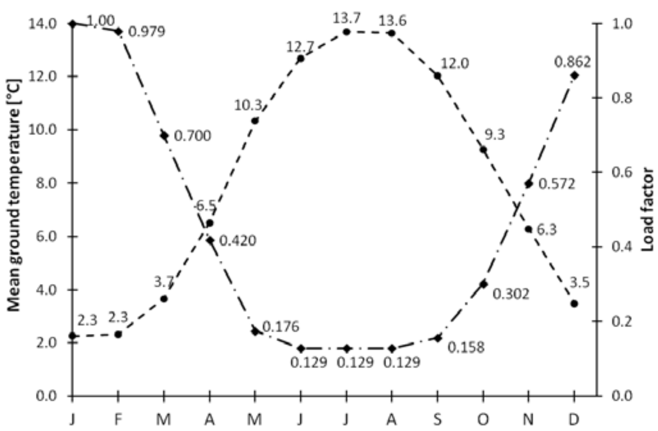

Fig. 1. Mean monthly ground temperature in Denmark (- - - Dalla Rosa 2011) and heat load factor (- · - ·) for the case with terraced houses.

The results from such simulations were compared to dynamic simulations in IDAICE 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 terraced houses and standard energy use. A typical summer day, during which heat is supplied only for the DHW preparation and the typical average day in January

(SH+DHW) are considered. 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 simulated low-energy DH networks for low-energy buildings to other reference example of DH networks in low heat demand areas.

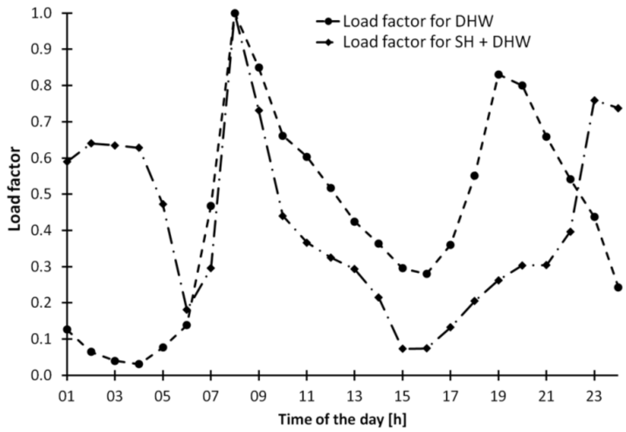

Fig. 2. Case with terraced houses and standard energy use. Load factors for a typical summer day (DHW only) and for the average day in January (SH+DHW). The peak values for the hourly energy use are 0.50 kWh and 2.45 kWh, respectively for DHW only and SH+DHW.

2.3 Degree of consumers connected to the district heating network

When planning a DH network for a new area in Denmark it is usually assumed that all the buildings in the area will connect to the new network. However, in reality not everybody connects, especially in the case of low-energy buildings since it is not compulsory for low-energy buildings to connect to DH, even if it is available in the area. This makes DH more expensive for the consumers that choose to get connected. For the DH network, it is therefore important to make a feasibility study of economical investigation of a minimal feasible degree of connected consumers to the 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 to the network. Degrees of connection were investigated by disconnecting 10% of consumers (4 buildings) in each step. Disconnection was done uniformly, always keeping the last consumer of the street connected, so that the total network length did not vary from case to case, thus keeping the DH network in such a way that it was representing a realistic case on the safe side.

Next, the cost analysis shows the minimal cost-effective degree of connection, which can be generalized in terms of linear heat density. The linear heat density is defined as the ratio between the heat demand and the length of the network.

3. Analysis

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 Space Heating (SH) demand. As seen in Table 2 (cases 1 and 2), having the same total energy use for lighting and equipment – but with load variations over the time, heating demand increases by 5% for both reference houses. This can be explained with the fact that during the night there is an increased heating demand in case of variable internal loads and the system has been heating up more than necessary for the following morning. In other words, the system is not able to respond so quickly. Another reason is that during the daytime, the amount of heat from internal gains and solar radiation that is produced is larger than what is required consequently the heating system shuts down and windows opened in cases of high temperatures. In this way some heat is wasted during the day, while during the night there is a heating demand that needs to be covered.

When for the terrace house having variable occupancy instead of constant occupancy, the heating demand decreases by 5% (case 2 – 22.5 kWh/m^2, case 3 – 21.4 kWh/m^2). That is due to the fact that variable occupancy with 3 persons results in bigger internal gains than 2 persons that are always present.

Table 2. Energy use in the reference houses for the different cases.

Case	Primary energy demand [kWh/m^2]					
	Light-ting	Equip-ment	Other	SH	DHW	Total
Terraced house						
Be06	/	/	4.7	23.5	16	/
1	21.7	7.7	4.3	21.4	16.4	122.1
2	21.7	7.7	4.3	22.5	16.4	123.2
3	21.7	7.7	4.3	21.4	16.4	122.1
4	21.7	7.7	2	14.6	16.4	109.6
5	21.7	7.7	4.3	43.7	16.4	144.4
Detached house						
Be06	/	/	2.4	19.2	15.4	
1	21.7	8.9	2.4	21.5	14.5	118.5
2	21.7	8.9	2.4	22.6	14.5	119.6
5	21.7	8.9	2.4	39.7	14.5	136.7

*Primary energy factor for electricity = 2.5; primary energy factor for heat = 1.

Usually, dwellings have CAV ventilation with fixed air flow all year around. Usage of VAV in the terrace house can lead to big energy savings, both for heating, decrease by 32% (case 1 – 21.4 kWh/m^2, case 4 – 14.6 kWh/m^2) and electricity needed for HVAC system, decrease by 53% (case 1 – 4.3 kWh/m^2, case 4 – 2.0 kWh/m^2). VAV also leads to smaller temperature fluctuations (there is no big temperature drop in the cold summer nights) and better indoor air quality with decreased CO_2 concentration (from max 800 ppm to 540 ppm) and smaller air age (from 3.4 h to 1.2 h).

Nowadays, dwellings have generally only CAV, which is also considered in Be06 calculations, as results indicate in table 3 (case with CAV has more similar energy use to Be06 case). Therefore all the next simulations are performed with CAV ventilation.

For comparison with case 5, which is representing realistic human behaviour, cases 1 and 2 were chosen. Case 1 represents standard simulations done by consulting engineers and case 2 represents more detailed simulations with variable internal gains. When including realistic occupancy and human behaviour models – case 5, the heating demand increases by factor 2 in comparison to standard calculations (from around 20 kWh/m^2 to 40 kWh/m^2).

Comparing the heat load for the standard (case 1) with the human behaviour (case 5) shows significantly affects on the magnitude of the heating peak load:

- +60% for the terraced house
- +27% for the single family house

In the following the focus of the analysis of the low-energy DH network is based on case 1, where the energy demand is calculated according only to building physics parameters and the simulation case 5, where the human behaviour is taken into account.

An interesting additional fact is that for low-energy buildings the heating season is approximately one month shorter than for standard buildings: that has an impact on the DH network operation.

3.2 Low energy district heating network supplying low-energy buildings

Based on the results from the analysis of the energy simulations of the two reference houses for case 1 (standard) and 5 (human behaviour) the analysis of the DH network in this section is performed. Some of the main parameters for analysing and comparing different networks are the heat production, the heat loss and the ratio between distribution heat loss/produced heat for each month of the year, which are shown in Fig. 3. In comparison to medium-high temperature DH networks (T_{supply}>=80°C) with low-heat density, the energy performance drastically improves. The low-energy DH concept is technically a fine solution both for terrace houses and for detached single family houses, having a share of heat loss on a yearly basis between 14% and 20% of the total heat production. Since there is an increased energy demand if human behaviour is taken into account, the ratio between the heat loss and the year-round heat production decreases typically from 20%, in the case of standard energy calculations, to 14%, if the human behaviour is taken into account. The energy from the pumps has not been included in the graphs since they only account for around 0.1% in relation to the total heat production for all cases.

The human behaviour has a significant influence on the network performance in the heating season. If the human behaviour is taken into account and compared to standard energy use, the total production increases from 35.8 to 57.4 MWh in January, in the cases of terrace house, while heat loss remains almost the same 4.8 and 4.9 MWh (Fig. 3/Tab3) (annual simulation). In addition the total operation of the network will become more feasible since the relative heat loss goes down from 13.5% to 8.9%, figure 3.

During the summer months the performance of the network is the same for different behaviour, since the heating system with variable loads is turned off. In the summer months the average relative heat loss is 29.7% in the cases with terrace house and 31.3% in the cases with detached house, figure 6. However DHW demand is higher in detached house (7.81 kWh per day) than in terrace house (5.12 kWh per day).

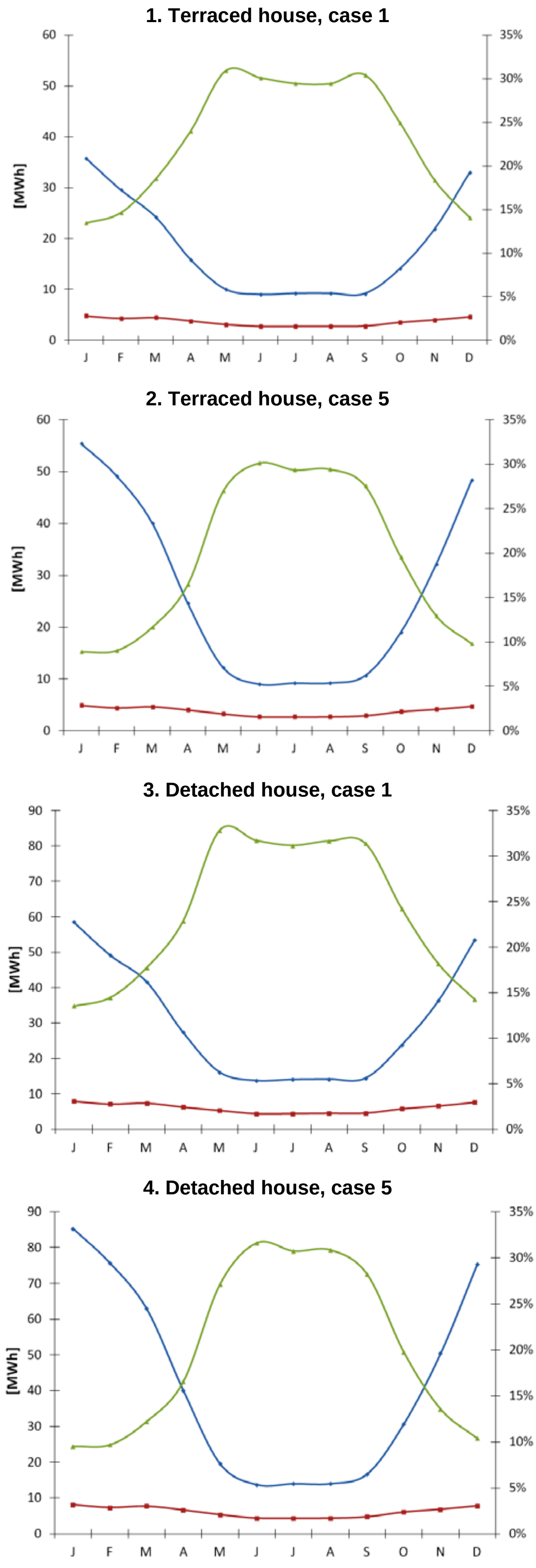

Fig. 3. Monthly heat production (blu), heat loss (red) and the ratio between distribution heat loss/produced heat (green).

The increased pipe length (by factor of 3) among the detached houses has a bigger influence on network performance than their larger heat demand, which results in higher relative heat loss in the DH network supplying the detached houses than the one serving the terrace houses.

Table 3. Comparison between network energy simulation with average monthly values and hourly values; January and July.

Type of buildings	Case	Total heat production		Heat loss	
		January	July	January	July
Simulation – Hourly [MWh]					
Terraced 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
Simulation – Annual [MWh]					
Terraced 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
Simulation – Difference [%]					
Terraced 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

The results show that it is very important to include the impact from human behaviour since it has a great impact on the energy efficiency of the network. When designing energy systems it is not enough to include only technological aspects: the end-users´ behaviour should be included. Since the user behaviour can result in significantly higher heat loads than the design values it is essential that the design of the network can handle this situation and not lead to underestimation. This can easily give the DH a bad image and could damage the implementation of $C0_2$ neutral communities, which would be most unfortunate since DH in Denmark plays a key role in the process of achieving the goals for reduction of the $C0_2$ level.

The final users need to have a significant participation and are very important to include in the process of implementing the vision of a fossil-fuel-free energy sector.

Energy demand in the buildings should be reduced as much as possible. However, with very low heat demand DH can be improved from an environmental point of view by increasing the heat demand with household appliances (using hot water in washing machines, dishwashers, etc.) changing the energy use from electricity to energy from DH.

Another issue is to estimate the accuracy of the annual simulations based on average monthly input values compared to detailed hourly dynamic simulations. The results show that annual simulations give sufficient accuracy when comparing to hourly simulations, however, the network during the summer period with small energy demand is more sensitive to load variations. In reality it can have up to 9% bigger total heat loss than with constant averaged load, based upon the usual calculations done by consulting engineers. 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.

The results were assessed to be sufficiently accurate, since both the building energy calculations and the DH network simulations were performed with the use of software which are reliable and widely use in engineering practice. A demonstration project has validated the applicability of the concept in Denmark (Olsen et al 2011).

3.3 Degree of consumers connected to the DH network

The following simulations were performed to investigate the performance of the low-energy DH network depending on the different percentage of low-energy buildings connected to the network. The results are illustrated in Fig. 4, and shows the ratio between distribution heat loss and total produced heat versus the linear heat density, where each point in the graph stands for the different percentage from 100% down to 10% of low-energy buildings connected to the network. The procedure was repeated with 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 terraced houses and energy use including human behaviour and the curve representing the case with detached houses and standard energy use.

As illustrated in Fig. 4, the heat loss are less than 20% of the heat produced, if the linear heat density is higher than 0.20 MWh/(m year). This demonstrates that if the line heat density is more than 0.20 MWh/m, it is possible to integrate low-energy DH network into the existing Danish DH networks without decreasing the performance of the whole network. On the other hand, it indicates the need for the majority of the buildings in such settlements to be connected to the common DH network, or else unacceptable economic and energy inefficiency is likely; this is particularly true for detached houses: in the case study at least 90% of the buildings must be connected to keep the cost of the energy below 20 c€ (excl. VAT) / kWh and the heat loss below 20% of the heat production.

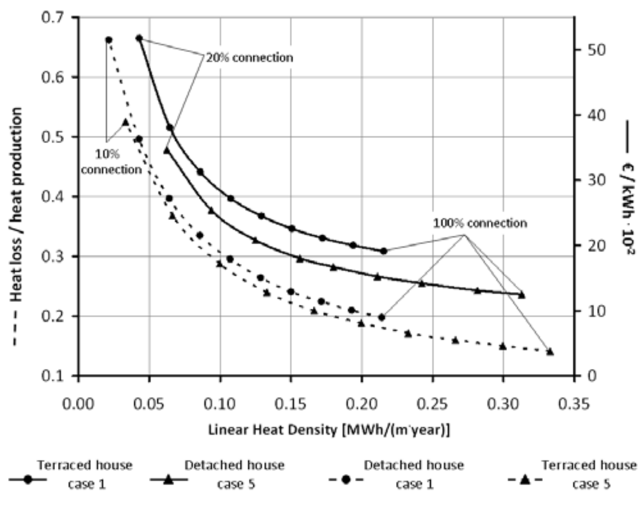

Fig. 4. Ratio between distribution heat loss and total produced heat versus the linear heat density (- - -). Specific energy cost (—). The picture shows the bottom and top curves. All the values lies between the top and bottom lines, for all the cases considered.

A study in Nordic countries, carried out by International Energy Agency within District Heating and Cooling Program (Zinko et.al. 2008), has showed that areas with a linear heat density of 0.3 MWh/m per year can be supplied by DH in a cost-efficient way. In our simulated cases the relative annual heat loss is below 15% for the linear heat density of 0.3 MWh/m per year, which means that low-energy DH network could be well integrated into the existing DH networks not only in Denmark but also in the other Nordic countries.

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 (derived from Danish District Heating statistics 2008-2009).

4. Discussion and Conclusions

In the future an increasing focus on designing the most cost-effective ways of coupling energy conservation policies will be needed. This can assure the implementation of $C0_2$ neutral communities. The consequences being a far more complex design of the whole energy system, where the focus needs to be not only on the single low-energy buildings themselves but on the whole society, since the future energy infrastructures are dynamic and climate responsive systems. As a consequence software will have to be able to work with such a level of complexity; however, there is a missing link in the development of these complex software solutions. In the paper it has been demonstrated how a link between a dynamic energy simulation program for buildings and a simulation program for District Heating (DH) networks can give supplementary important information in the design phase.

When designing CO_2-free societies rather than only single low-energy buildings it will in many cases be more economical to produce for instance hot water at central locations rather than local in the building. This is due to the fact that in most of the cases few low-level temperature resources are available for a reasonable cost for the local buildings. To heat water at low temperatures using oil, natural gas or electricity is from an energy efficiency point of view wasting of resources. In these cases DH plays an important role in Denmark since it covers 62% of the heating demand. By using low-temperature DH one of the advances is that these low temperature level heat sources only result in little CO_2 emission or are CO_2 neutral, and that the cost is much lower as a result of the lower specific costs for large plants. An example of this is using renewable energy from solar panels for heating low temperature hot water, where the cost for the individual buildings can be three times more expensive compared to large scale solar panels systems for DH (Ulbjerg F. 2003).

By using a dynamic energy simulation program for buildings it was possible to analyze the influence of the human behaviour for the building and link the results to the simulation program for District Heating (DH) networks. The results show that human behaviour 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. The consequence is that in order to get the full potential of the energy saving in the society it is very important to address the decisive involvement of the end-users. The human behaviour is the factor that affects the most the energy use in low-energy buildings and should be included in energy simulations. The results can then be linked to programs simulating the energy supply system in order to support the design of CO_2-free communities. The cases considered, although referring to the Danish tradition in the construction sector and to the Danish climate, have a general value and are adaptable to other situations and countries.

The results demonstrate that there is a large potential for distributing energy in areas with energy efficient buildings. As a measure for the feasibility of DH, the linear heat density can be used as a representative value, and the results show that it is possible to supply heat with low-energy DH networks in a cost-effective way in areas with linear heat densities down to 0.20 MWh/(m·year). Even in cases where the user behaviour is not optimal, the system is able to deliver heat to each customer.

In the future all new buildings in Denmark will be low-energy buildings, and all analysis and building regulations have to be according to this. In the 1970-ies in Denmark building regulations were introduced, which gave special possibilities for builders of low-energy buildings to decide, which kind of energy source they wanted in their house since the energy use was considered low. This was a privilege given to encourage people to spend extra money on the building constructions in the process of designing low-energy buildings, and then permit them to use electricity for heating since it was cheap to install and use. It has later been forbidden to use electricity for heating, however the builder still have the privilege not to connect to the DH network. The analysis shows that this is a key problem, which needs to be addressed by the politicians in Denmark since the linear heat density is increasing with number of connected consumers to the DH network. It is necessary that the majority of the buildings in the future low-energy buildings need to be connected to the common DH network, or else unacceptable economic and energy inefficiency are likely. This is especially true for detached houses, where at least 90% of the buildings must be connected. Since it is not mandatory to link to the common DH network it gives insecurity in the design of the DH network, and the goal of a CO_2-neutral society. In many cases using CO_2-neutral energy sources is a challenge from a pure economical point of view; however from an economical point of view changing the law to make it mandatory in DH areas to connect can be done at reasonable cost. This is an important issue since the implementation of an energy system that fully relies on RE needs substantial capital investment, which in the long-term period could be sustainable, from the environment and socio-economical point of views.

The low-energy DH concept could be strategic for reaching ambitious energy and climate targets and has the potential for being widely implemented in Europe, taking into account what concluded in (EcoHeatCool project 2006) about the European heat market. Similar conclusion can be drawn for other countries where energy saving measures and efficiency in the energy supply agenda are priorities in the political agenda.

In the perspective of a 100% RE-based heating sector, the article explored the opportunity to apply community energy systems optimized to supply low-energy buildings, since there might be the chance that such concept can be more cost-effective than single-building-oriented concepts (in specific conditions). It would be beneficial to find the optimal border between the proposed systems and high-efficiency local energy generation. This idea has shown to be promising in Denmark and it could be interesting to investigate its applicability elsewhere. No general conclusion can be deducted in absolute terms, though. The paper aims at stimulating such discussion.

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