Modeling and Simulation of a Heating Mini-Grid for a Block of Buildings

Abstract

Termonet is a new concept based on the use of individually adjustable and collectively managed ground source heat pumps, connected to a thermal grid with non-insulated piping supplying heating/cooling demand of households located far from existing district heating grid (GeoDrilling, 2017; Pellegrini and Bianchini, 2018). Production and consumption profiles from Termonet dynamic simulations using an object-oriented modelling approach are compared to insulated ground source and district heating networks with extra-small consumer density encountered at test sites in Denmark. The hypothesis of the reduced production requirements in Termonet is tested and the identified pros and cons indicate the direction for small-scale thermal grid development with emphasis on efficiency and control.

Introduction

The heating and cooling in buildings and industry accounts for half of the EU energy consumption (European Commission, 2016) and global energy demand constitute a significant factor in international economy and ecology. This makes efficiency and sustainability decisive criteria of modern energy system design. Conventional central heating systems were traditionally limited in both criteria and had to be modified to include waste heat management (Persson and Münster, 2016), cogeneration (Colmenar-Santos, 2016), low-temperature applications (Averfalk and Werner, 2018) and grid balancing in heating and cooling markets (Ito et al., 2017). Resulting decentralized district heating and cooling systems have already proved their effectiveness in some EU countries like Denmark and Sweden aggregating heat loads to progressively optimise the energy supply and switch to more sustainable fuels (Fernandez, Roger-Lacan, Gahrs and Aumaitre, 2016). The use of ICT technologies gradually turns District Heating networks into thermal analogues of Smart Electricity Grid, also referred to as 4th generation District Heating (4GDH) and described by Lund et al. (2014) and Lund et al. (2018).

Until recently, the benefits of this development were primarily enjoyed by cities and other settlements located near district heating transmission/distribution grids. However, the emerging technologies create options to include regions with low consumer densities in 4GDH, which was not possible for 3GDH. Importantly, heat pumps are likely to substitute most of oil and gas boilers in Smart Grid (Nørregaard, Foged, and Olesen, 2015; Vermeulen and Willemse, 2016; Fischer and Madani, 2017) due to environmental and economic reasons. In this relation, the small- and medium- size heat pumps can be used to make distant regions independent from central/district heating and local solutions, which are not in line with the Sustainable Development (Sachs, 2015). The ground source heat pumps are especially attractive in this respect due to

- high efficiency, including stable performance at low temperatures and changing environmental conditions,
- freely available ground energy pumped with moderate amount of electrical energy,
- that it enables electrification of the Danish heating sector promoting the integration of wind and solar power,
- potential for balancing production and demand,
- independence from central or district heating.

The last fact is especially important for rural communities, because it provides a way for them to be included in the overall progress and give opportunity to establish their own heating and cooling economy. On the way to energy independence for separate rural settlements, multiple research projects are launched around the world involving, apart from heat pumps, electrical vehicles, smart controllers and sustainable economy schemes (Aarup et al., 2014). In particular, the important concept called Termonet (GeoDrilling, 2019) emerged in Denmark to describe ground source heating networks, which will allow small cities to satisfy their own needs in heating and cooling by arranging sustainable energy parks owned by the inhabitants in line with 4GDH and Smart Grid principles. In this paper, we describe the Termonet concept, create a model of Termonet test site and compare energy production, distribution and consumption in Termonet to those in insulated small- and large-scale district heating networks.

Termonet concept

Conventional district heating relies on the Economy-of-Scope (Frederiksen and Werner, 2013) relating to district heating's fundamental idea to use local fuel or heat resources, that otherwise would be wasted, to satisfy local customer demands for heating. Consequently, certain district heating sectors depend on large-scale electricity production to either run the industries, which produce excess heat, or to pump geothermal energy.

In near future, local sustainable electricity production can become a reality. In this case, the ground source heat pumps have a strong chance to become the primary resource for space heating and hot water preparation in small districts below 100 households with underfloor heat exchanger (UFH) as a potential emitter. Termonet as a concept generalizes and explores thermodynamic and economic characteristics of these small districts for creating a sustainable and efficient infrastructure with integrated ICT solutions and price-based control of storage and consumption. This will allow to go beyond the Economy-of-Scope in traditional district heating and supply low-density areas with high efficiency heat, owing to different approach to storage, transport and recovery of energy in non-insulated horizontal piping.

The Termonet concept is based on five ideas:
1. completely cover heat demand of a district by a vertical borefield
2. reduce investment cost by using non-insulated pipes for distribution/transmission
3. optimize low-temperature supply to benefit from the uninsulated horizontal pipes used as a heat source
4. use seasonal storage to cover both heating and cooling demands (including underground water)
5. use model-based control to minimize the price and borefield depletion (optional)

The Termonet modeling is important for design optimization and potentially, for model-based control. The latter should rely on a fast and robust dynamic model, which is able to simulate the network status in real time and be integrated with ICT software and hardware. Dymola is a suitable framework to create and simulate such models, whereas the model-based control can be implemented using a Functional Mockup Interface.

The hypothesis for this paper is, however, related to points 1, 2 and 3 and is formulated as follows: heat gains from the uninsulated horizontal pipes can reduce the total yearly heat loss in distribution pipes and, as a result, decrease the borefield production and depletion; this will give Termonet advantage over the insulated and district heating networks in regions without district heating. This hypothesis will be tested on Termonet test site model described below.

Termonet test site

The distribution network, simulated here, supplies energy demands of the two residential buildings located at the test site in Southern Denmark, by transporting the heated fluid from three borehole heat exchangers (BX) to the cold side of a heat pump located inside each building. The two buildings are assumed identical in simulations, because detailed information for only one of them is available. The soil and borehole properties are taken from the thermal response test (TRT) conducted in the area and the description of pipe interaction with the soil is based on the same data. The model of the heat pump was calibrated using genetic algorithm (GA), where parameters were estimated from data collected at the test site in 2017. All the test site data including TRT and sensor measurements was provided by company GeoDrilling (GeoDrilling, 2019).

Methods

The following object-oriented models are created and simulated in Modelica language-based software Dymola to compare Termonet to insulated ground source and district heating networks:

1. Termonet: model with a single-consumer with a non-insulated pipe (conductance 2.8 W/(m² K)) representing distribution network and a borehole representing heat production,

2. Insulated pipe network: the copy of a single-consumer Termonet model with decreased pipe conductance, 0.032 W/(m² K),

3. District heating network with a heat pump: Copy of model 2, where the production is changed from borehole to an ideal heater with fixed temperature outlet of 70 ℃,

4. District heating network with prescribed consumption: copy of model 3 with a heat pump substituted by an ideal heater with controlled load,

5. Termonet: two boreholes, two consumers and two non-insulated pipes all copied from model 1.

As a basis for these models, Termonet package was developed by reusing components from IDEAS, Buildings, and Standard Modelica Libraries (Modelica Association, 2019).

Termonet with a single consumer

The model of the single-consumer Termonet is shown in Figure 1. At the highest level, the double-U borehole component `borehole` based on the line-source model developed by Bauer et al. (2011) has been taken from IDEAS Library. The weather datablock `weaDat` supplying the ambient temperature values to the building `termonetUnitValidated` on the right of the figure and buried pipe `buriedpipe` in the center of the figure is taken from the Buildings library and was used with mos-file containing Copenhagen weather conditions throughout 2017.

Figure 1: Model of the single-consumer Termonet.

Figure 2 shows the implementation of the Termonet consumer component with two hydronic loops. The lower (ground) loop is connected to the evaporator of the Carnot heat pump `heaPum` from IDEAS library and the upper (UFH) loop is connected to its condenser. The heated water is run by a mass flow-controlled pump `pu2` from the condenser to the UFH represented by a radiant slab `sla` taken from Buildings library. The slab consists of 5 layers, where the water pipe is imbedded between the

second (scrid) layer and third (Nexxa panel) layer. The heat extracted from the water is emitted to the building's thermal mass, which exchanges heat with the ambient through the total wall resistance. In the lower loop, the speed-controlled heat pump `fan` runs 20% ethanol glycol through the borehole heat exchanger located outside the building. Both pumps and the heat pump are PID-controlled based on the room temperature set point.
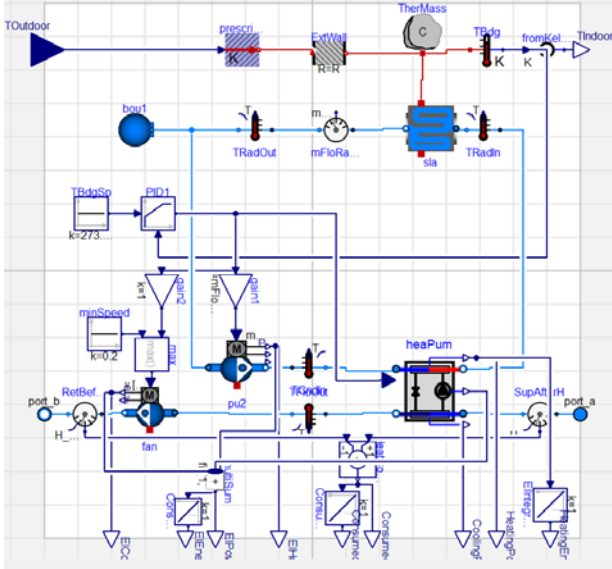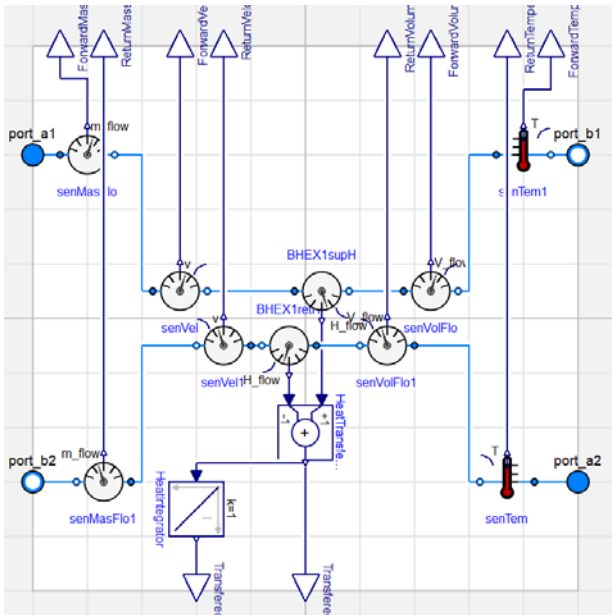

Figure 2: Model of the Termonet consumer.

Figure 3: Model of the Termonet sensor

The borehole and consumer in Figure 1 are connected to the Termonet fluid sensors F1 and F2, which measure the energy transferred in the flow from the left pair of fluid connectors in the Figure 1 to the right pair of fluid connectors during the time passed from the simulation start. The implementation of the sensor is shown in Figure 3. Additional to energy, the sensors measure fluid temperatures, mass and volume flow rates, flow velocity in the supply and return pipes and the transferred power. To calculate energy, enthalpies of flows in the supplied

and the return pipes are measured and subtracted to find the transferred power, which is subsequently integrated from 0 s to current simulation time.

Figure 4 shows the implementation of the Termonet distribution pipeline based on the pipe models from Buildings library located in the center of the figure with energy and mass balances implemented using finite volume discretization. Each pipe is influenced by changing ambient temperature boundary condition supplied through the top blue information connector into the ground layer. The latter is modelled as single heat capacitor and two thermal resistors and is coupled to the pipe wall through its heat port. Through the same heat connectors, each of the pipes is coupled to the ground elements below them (the seasonal zone extending down to 30 m in depth). Both of the ground elements are connected to the fixed temperature boundary condition (7.7℃) in the bottom of the model representing the undisturbed ground layer (below 30 m). The round heat flow sensors measure the power lost by each of the pipes via two channels: to the ambient and to the undisturbed ground. These heat flows are summed to give the power lost in the pipes, which is then integrated from 0 to current simulation time to calculate the lost energy. The model 2 of the insulated network is identical with the described Termonet model and differs only in pipe insulation conductivity value.
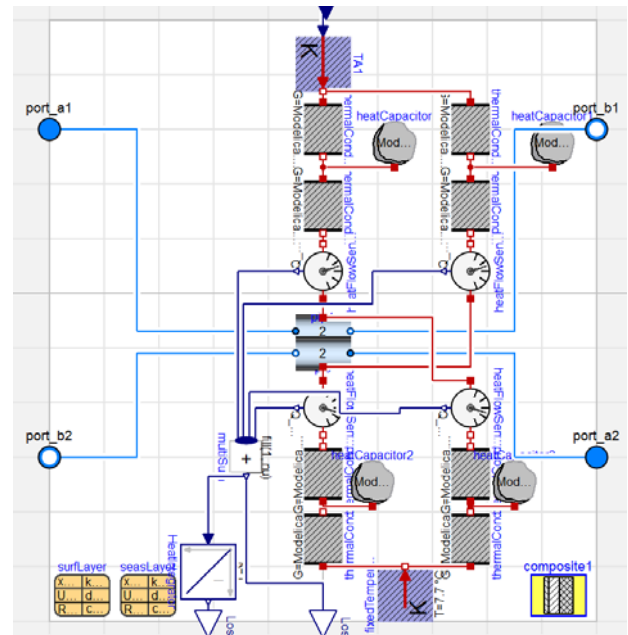
Figure 4: Termonet distribution/transmission model.

District heating with a single consumer

The model 3 of the single-consumer district heating network with individual heat pumps installed at the consumer side is shown in Figure 5. The only change compared to Termonet is an ideal heater from IDEAS library with fixed temperature outlet of 70 °C prescribed through information connector.

Figure 5 may also represent model 4 of the single-consumer district heating network with prescribed

consumption, because it is identical on its top level to model 3.
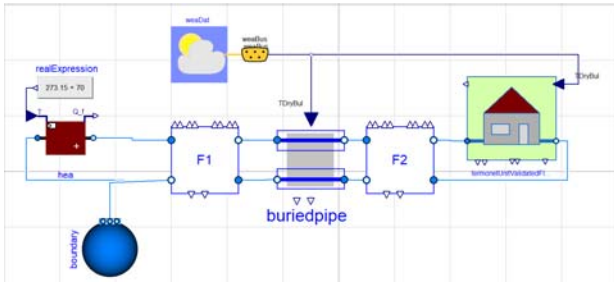
Figure 5: Network with prescribed consumption

The difference is in the consumer model implementation, shown in Figure 6, where the load (consumption) on the network is modeled as a pair consisting of an ideal cooler and ideal heater. Cooler extracts the fraction of peak demand prescribed by PID signal from the district heating loop, while the heater supplies the same amount of heat to the thermal mass of the building. The peak demand is taken from the yearly simulation of model 2 for insulated network.
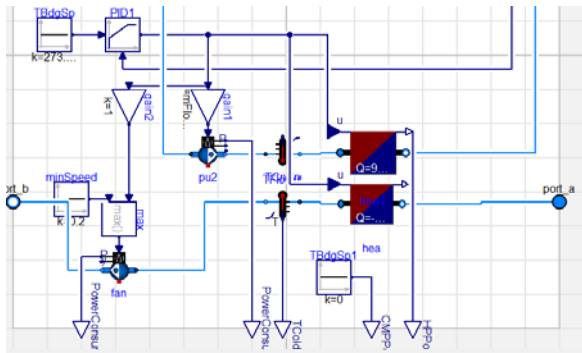
Figure 6: Consumer with prescribed consumption

Termonet with two consumers

In the Termonet model with two consumers both boreholes B1 and B2 and consumers H1 and H2 are connected in parallel as shown in Figure 7. All components are identical with components from a single-consumer Termonet model, including parameter values, shown in Table 1. The Termonet sensors F1, F2, F3, F4 and F5 are placed between each pair of components to monitor energy transfer in different parts of the network.
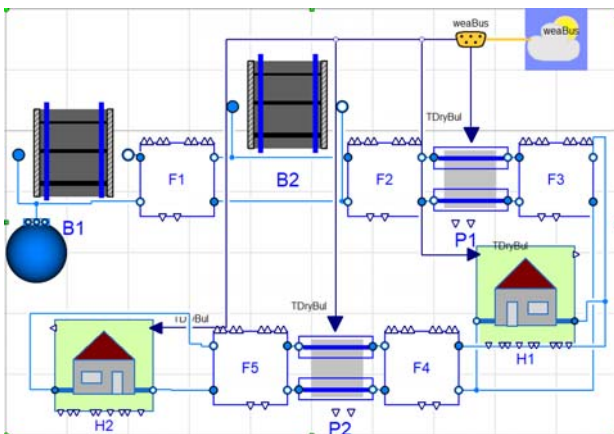
Figure 7: Termonet model with two consumers

Table 1: Termonet model parameters.

Parameter	Value	Source
pipe length	50 m	Test site/assumed
pipe depth	1 m	Test site
seasonal depth	30 m	TRT
external pipe diameter	0.05 m	Test site
pipe thickness	0.002 m	Test site
Insulation thickness	0.03 m	assumed
distance between UFH pipes	0.2 m	assumed
UFH 1, timber	18 mm	assumed
UFH 2, screed	30 mm	assumed
UFH 3, Nexxa	31 mm	assumed
UFH 4, screed	50 mm	assumed
UFH 5, concrete	100 mm	assumed
BX height	90 mm	TRT
BX radius	0.089 m	TRT
BX tube diameter	0.032 m	TRT
BX tube thickness	0.0015 m	TRT
shank spacing	0.03 m	TRT/assumed
total floor area	170.9 m^2	Test site
soil conductivity	2.8 W/(m K)	TRT
filling conductivity	2 W/(m K)	TRT
tube conductivity	0.38 W/(m K)	TRT
Pipe insulation conductivity	0.032 W/(m K)	Test site
Soil specific heat	810 J/(kg K)	assumed
filling specific heat	1000 J/(kg K)	TRT/assumed
pipe specific heat	1850 J/(kg K)	Test site
thermal mass	163 MJ/K	Test site/assumed
soil density	2700 kg/m^3	assumed
filling density	1650 kg/m^3	TRT/assumed
pipe density	958 kg/m^3	Test site
wall resistance	0.117 K/W	Test site/assumed
BX resistance	0.07 K/W	TRT
nominal evaporator temperature	10 ℃	GA
nominal Condenser temperature	40 ℃	GA
DH supply temperature	70 ℃	assumed
Indoor set point	21℃	assumed
undisturbed ground	7.7 ℃	TRT
nominal COP	2.5	GA
borehole fluid	20% ethylene glycol	assumed
floor pipe	PEX_DN_100	Test site
pumps	WiloStratos25/1:4	assumed
nominal compressor power	1500 W	GA

The "assumed" parameters in Table 1 were chosen by authors based on ether educated guess or small-scale district heating practice (REHAU, 2014; Warmup, 2014).

Results and discussion

Termonet compared to insulated network

Figure 8 shows comparison in yearly variations in heat produced by the borehole (black colour, measured in F1)

and lost in distribution pipes (red colour, measured in P1) for single-consumer Termonet (solid curves) and non-insulated network models (broken curves). Termonet loses more energy in winter and gains more energy in summer, than the insulated network (broken lines).
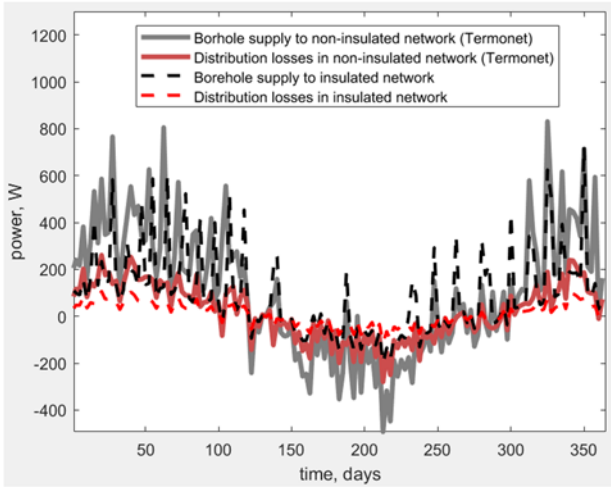

Figure 8: Power produced and lost in Termonet in 2017

As a result, production increases in Termonet in winter to compensate for the increased losses. The adverse effect of this is a possible borehole depletion and, therefore, this effect can be undesirable. Corresponding energies, plotted in Figure 9, have steeper maximums and minimums for Termonet, corresponding to the transitions between the cold and warm seasons. In winter, the losses and borehole production in the Termonet exceeds those in the insulated network to more than 500 MJ and 1 GJ, respectively. Although for larger times, the difference reduces considerably due to summer gains, the differences in energies return to around 500 MJ in the end of the year. This corresponds to 20% savings on production and 60% savings on heat losses when using insulated pipes and raises a question whether Termonet can compete with the insulated network.
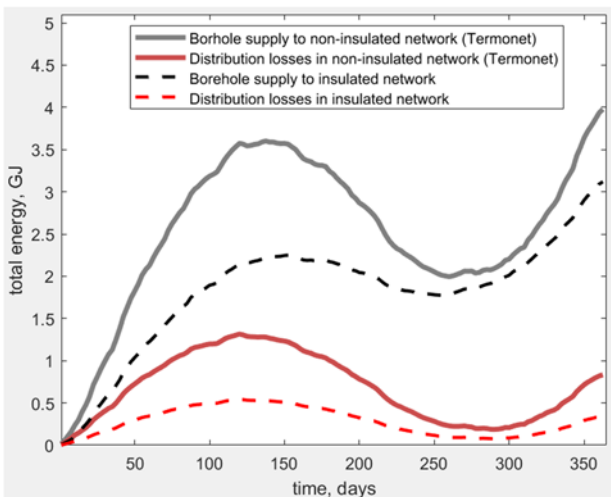
Figure 9: Energy produced and lost in Termonet in 2017

Apart from this, the increased borehole usage should lead to depletion periods, when no heating is possible. This, however, is not observed in the test site measurements (GeoDrilling, 2019). It is observed that no depletion

occurs and the yearly heat demand of block of buildings is covered without any problems.
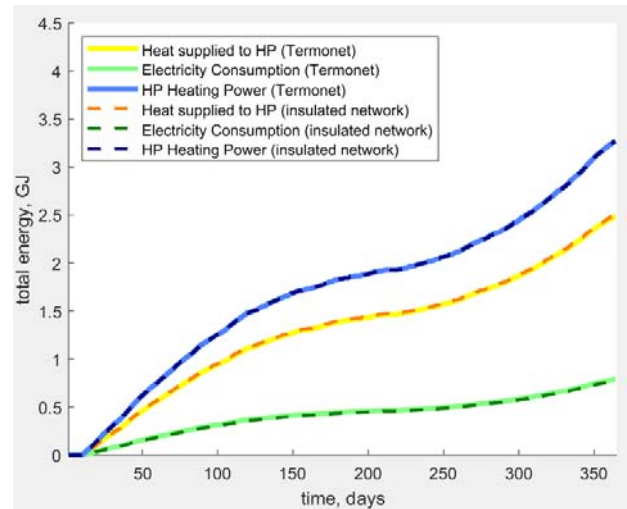
Figure 10: Energy demand and consumption in Termonet

Finally, to ensure that the comparison of production and losses is fair, the integrated energy flows on the demand side measured in F2 (yellow colour) and in H1 (blue and green) are shown in Figure 10 and are observed to have close values in both cases. The observed behaviour suggests, that the boreholes may be overmentioned, which needs further investigation. Here, the yellow curves correspond to the heat drawn by the cold side of the heat pump from the distribution grid, blue curves to the heat supplied by the heat pump to the UFH system and green curves to the total electricity consumption of the pumps and heat pump. Although the total energies are the same with relative error below 1%, there is a difference in corresponding power dynamics as can be seen from Figure 11, where the same colours denote powers of Figure 10 calculated in the specific period between February 14 and March 1.
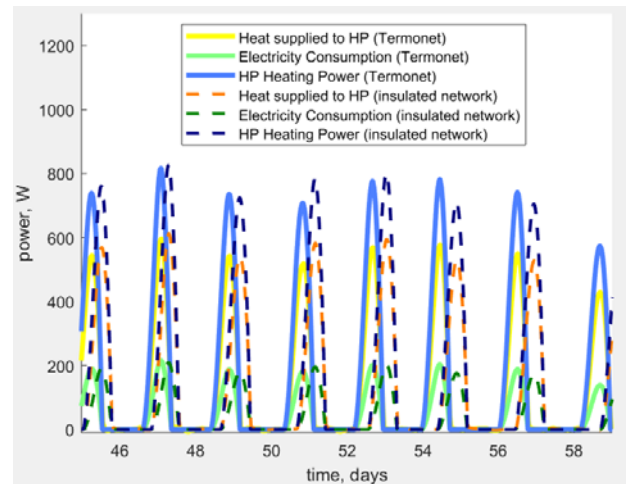
Figure 11: Power demand and consumption (weeks 7-9)

This delay is explained by the large thermal mass of the building and the poor tuning of the PID controller. The corresponding indoor temperature oscillates with the approximate amplitude of 0.04 K and period of 2 days. The thermal power consumed and produced by the heat pump in Termonet are close in magnitude to

corresponding non-insulated network values exceeding them at specific time moments.

The system COP is calculated as the ratio between the heat supplied and the electricity consumed by the heat pump and is shown in Figure 12. Both networks have the same COP profile, but the magnitude is always larger for the insulated case. It can be noticed that same 2-day dynamics is produced in the figure.
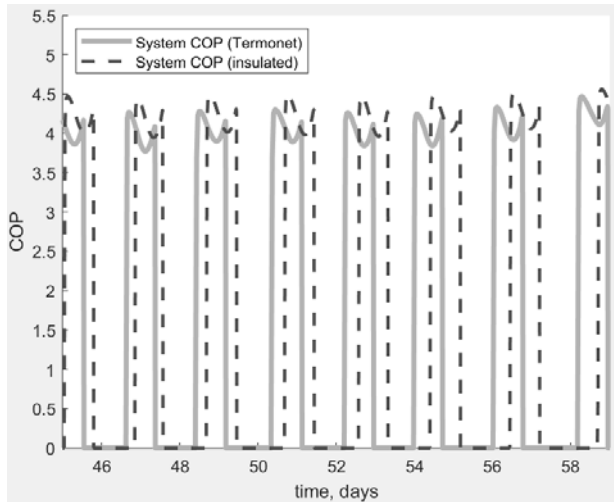

Figure 12: COP=Heating/Electricity in weeks 7-9

Termonet compared to district heating network

Figure 13 shows comparison of Termonet production and loss to the insulated district heating network model values. In this case, it turns out that the powers in district heating network are higher than in Termonet.
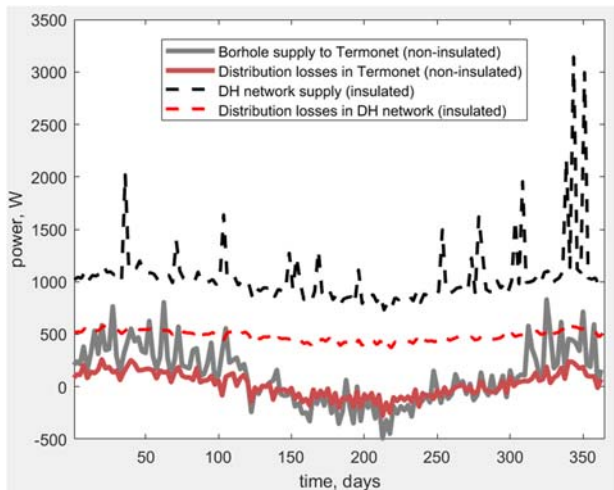
Figure 13: Power produced and lost in district heating network during 2017

This is expected, since the district heating economy is viable if a large number of consumers is involved and become completely unprofitable, if only one consumer is considered. For the intermediate case of small number of consumers corresponding to small heat density in considered area (typically below 20-50 kWh/m²), the district heating will likely not be considered feasible due to high annual distribution capital cost, which is inversely proportional to the linear heat density (Frederiksen and Werner, 2013). The average level of losses for district heating seen in the figure is above the average level of production for Termonet and the district heating production is approximately three times larger. The corresponding energies, shown in Figure 14, do not go through maximums and minimum, but increase almost linearly. This results in 88% total savings on production and 95% saving on consumption in Termonet compared to district heating.
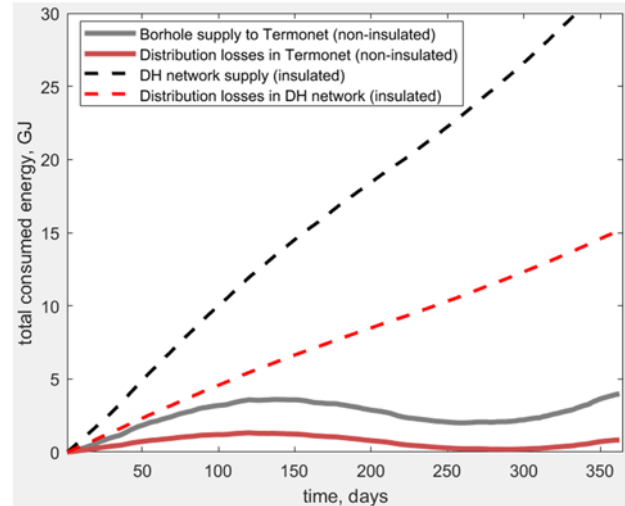
Figure 14: Energy produced and lost in district heating network with prescribed demand during 2017
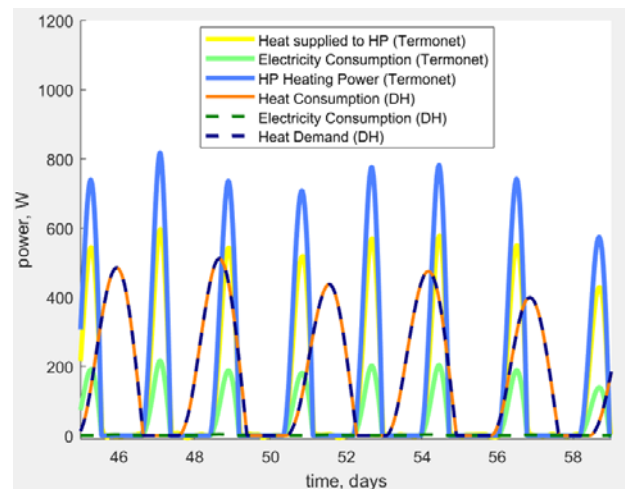

Figure 15: Power demand and consumption in district heating network with prescribed demand in weeks 7-9.

As Figure 15 shows, the dynamics at the consumer side is rather simple due to the lack of dynamic devices, like a heat pump or heat exchanger, which would produce heating at the expense of an increased electrical power consumption. The demand is fixed in the model and is defined as the fraction of the peak heating power calculated for the insulated heating network considered in previous section. Correspondingly, the amount of power supplied to the building (demand) is equal to the amount of power extracted from the distribution grid (consumption). In this case, the electrical power is consumed only by pumps, which contribution within the system is negligible with good approximation. As far as the consumer economy is concerned, there will be no associated expenses contributing to the cost. The

interesting feature of the consumer dynamics compared to the insulated ground source network is a larger shift and additional broadening of the maximums. The valid explanation for this would be that the heat capacities and resistances associated with storage and heat exchange in the borehole and heat pump are substituted by a fixed-temperature heater on the production side and prescribed demand on the consumption side. The remaining contribution to the system's time constant originates solely from the pipe-to-ground and floor-to-construction subsystems.
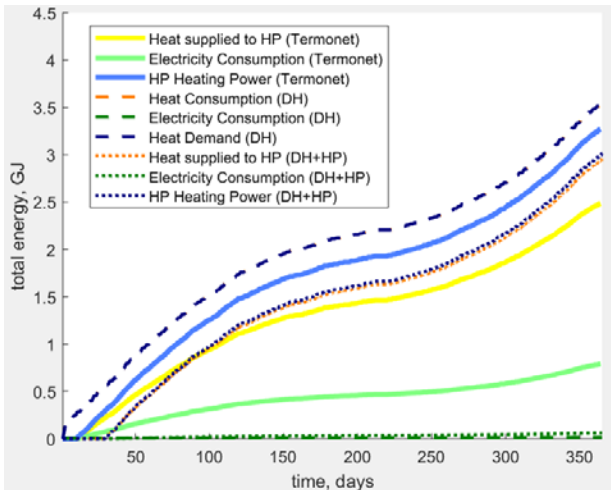
Figure 16: Energy demand and consumption in district heating networks in weeks 7-9.

Although the peak values lie lower for district heating than for Termonet, the broadening leads to the situation, when the integrated energy demand and consumption is larger for district heating network, Figure 16. In the Figure, another (third) case is added to comparison, where the district heating network is combined with the heat pump (model 3, dotted lines). It turns out that the integrated values for heat pump-based district heating are reduced below the conventional district heating values.

Termonet with two consumers

Figure 17 shows simulated energy flows for Termonet with two consumers H1 and H2 and two borehole heat exchangers B1 and B2 in the configuration shown in Figure 7. The parameters of the consumers and boreholes are chosen the same to reduce the number of factors which may obscure analysis. As a result, the heating power and electricity consumption of the heat pumps as well as heat extracted from the network have close values for both consumers. However, the second consumer draws less heat, which is also manifested in the larger electricity consumption. This happens because the heat pump COP for the first consumer is slightly higher than for the second consumer.

Due to temperature drop in the loop, the pipe losses associated with the second (cooler) pipeline P1 are reduced compared to the first (hotter) pipeline P2. The amount of heat transferred from the heat pump to the building stays approximately the same due to the prescribed energy demand in the upper loop and the PID controller.
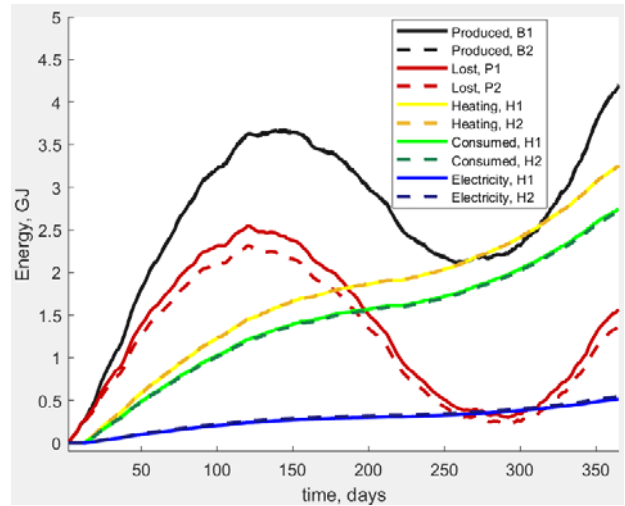

Figure 17: Energy flows in the two-consumer Termonet

The temperature differences along the pipeline behave as expected. Figure 18 shows the temperature drop T3-T2 along the return pipe in Termonet, where T2 and T3 are the temperatures measured by meters F2 and F3, respectively, and compares it to that in the insulated network. The temperature drop in Termonet exceeds the same temperature drop in the insulated network during cold periods and goes below that in summer. This stays in agreement with the fact that the Termonet pipe mostly lose energy to the ground during the winter rather than getting it from the ground.
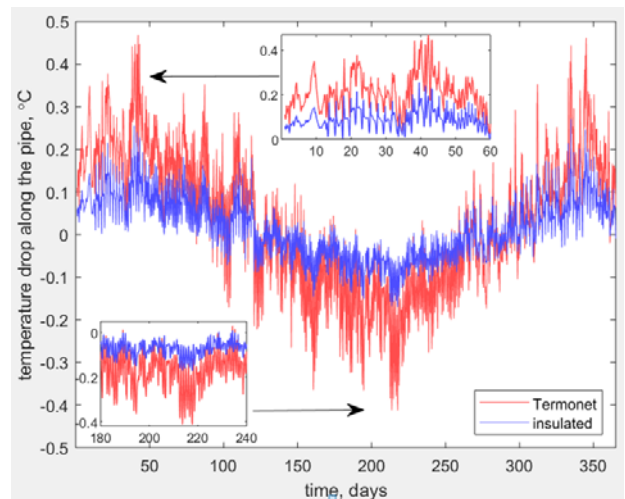

Figure 18: Temperature drop in P1 return

Conclusion

This paper has investigated the hypothesis whether the Termonet as a non-insulated heating network based on ground source heat pump can produce energy benefits for the low-density areas as compared to: (a) conventional thermal network with insulated distribution pipe and ground source heat pump, (b) conventional district heating network with constant temperature with 70-degrees supply and prescribed consumer consumption, (c) the same district heating network with installed heat pumps. It has been found that the Termonet can provide the required thermal comfort in the residential building but suffers from highly increased total annual energy

losses and production differing by around 500 MJ from those in the insulated network, which does not well agree with experiments at the Termonet test sites. In other words, the hypothesis of the advantage of non-insulated network, such as Termonet, cannot be argued from point of view of the presented Modelica model and further investigation is necessary to explain the real behaviour. However, model gives valid results for the dynamics of subsystems and different results are consistent. Additionally, it was found, that compared to the district heating network, Termonet provides important advantages, when considering small districts and low population density. Both losses and production in district heating system with the same parameters are boosted in comparison to Termonet due to higher temperature supply maintained in the district heating network. Additionally, due to more "flat" dynamics of the network corresponding to the absence of the local heat sources with faster dynamics, the district heating network was shown to provide higher consumed energy on a single household level.

As an outlook, it would be important to track the correspondence between the non-insulated (Termonet) versus insulated networks and small-scale (Termonet) versus large-scale district heating depending on the number of consumers and the distance between them. Other important questions that were left out of the present study are the underground seasonal storage, influence of underground water flows, integration of renewable electric sources with ground energy.

Acknowledgement

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