Real operation data analysis on district heating load patterns

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Abstract

District heating networks play an important role in the heating and cooling sector, serving up to 60% of the citizens in some countries. The availability of a thermal network supplying multiple users allows producing heat from different sources and multiple technologies. The possibility of relying on different solutions allows the system manager to optimize the heat generation by choosing the best unit for each operation condition. This choice is based on a deep knowledge of heat load profiles, that are related to users behavior, network performances and control logics.

This paper provides an analysis of a DH system operation over ten heating seasons, with the aim of highlighting the main characteristics of the heat load variations and finding the fundamental drivers for heat load prediction. Although the system has seen a significant development throughout the years, the specific energy consumption has been found to be comparable on the whole duration of the analysis. Two main patterns are highlighted, based on the different operation settings along the hours of the day and the outdoor temperature as the main weather driver for building's heat demand.

Keywords: District heating, Data analysis, Operation, Energy signature, Heat loads

1. Introduction

District heating systems have been developed in last decades as an effective way to supply heat to final users, especially where combined heat and power plants provide a high conversion efficiency. Within the current European targets on energy efficiency [1] and energy production from renewable sources [2], DH systems can play a major role through sustainable and efficient thermal energy production, within the Smart Thermal Grids concept framework [3, 4, 5, 6].

DH systems have a wide field of applications, ranging from large systems supplying heat to the major metropolis to small systems tailored on mountain villages or isolated communities. The heat production comes from different sources, depending on the size of the system and on the location. Large DH systems usually rely on CHP production from fossil fuel-based plants, exploiting the higher efficiency provided by cogeneration with respect to separate production of heat and power. In some cases, the heat is produced from waste incinerators or from large biomass plants, especially in northern Europe. Medium and small DH systems show a wider variety of energy conversion technologies, ranging from fossil CHP production to biomass heat or CHP production [7, 8],waste heat recovery from industrial sites, heat pumps, energy generation from geothermal sources [9, 10] and solar energy [11, 12].

Many literature works addressed the development of simulation models and tools for the design and optimization of DH systems, considering both energetic aspects and economic aspects (among others, [13, 14, 15, 16, 17]). These models provide different approaches to increase the energy efficiency of the DH systems, comparing technologies, system layouts and configurations. Some works are focused on the role of energy storage systems, which provide an effective way to help decoupling the energy production and the energy demand, with the aim of increasing the DH system efficiency [18, 19, 20].

In the last years, demand load assessment and management has become more and more important, as the users' behavior can have a significant impact on the global efficiency of the system. In particular, the heat load pattern of the single substations is a major concern for a correct and effective DH operation and management. In addition, environmental aspects need to be taken into account, as the development of DH systems should provide environmental benefits together with the increase of energy efficiency. While a decrease of CO_2 emissions can generally be obtained, the emissions of other pollutants could need a dedicated analysis [21, 22, 23].

While much attention has been paid on the design and optimization of future networks, few works address the operation analysis of existing DH systems [24, 25, 26, 27]. However, the operation and control settings can have a significant impact on the primary energy consumption of the DH system, as over the year the system operates in different off-design conditions, especially at partial loads.

This paper provides an analysis of an existing large-size DH system, supplied by natural gas CHP units and integration boilers. The possibility of considering several

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years of operation with a narrow time step gives the opportunity to perform a statistical analysis over various operation conditions. A correlation is proposed between the DH system consumption in different operation conditions with respect to the outdoor temperature of the site, by applying the energy signature methodology.

2. Methodology

2.1. Description of the case study

The DH network considered in this work is supplying the city of Turin (about 900,000 inhabitants), in the north-west of Italy. The DH system has been continuously evolving in last decades: the first users of the DH system were connected in 1982, when a CHP unit started to produce electricity and heat in a northern district of the city. In the following years, different production sites were connected to the grid, and the size of the network and number of users have continuously increased. Turin DH network currently serves about 56 million cubic meters of buildings (almost 60% of the total buildings in the city), with a network extent larger than 500 km of dual piping (as of 2014). The total amount of heat produced in 2014 was 2.0 TWh, and 1.7 TWh of energy was supplied to the final users, resulting in about 16% of thermal losses of the network[28]. The main part of the connected users are residential buildings (about 75%), while the remaining part is composed by public administration offices, schools, hospitals and commercial buildings. The total area served by DH network is shown in Figure 1. The heat production is provided by multiple generation units, both CHP and integration boilers. The newest CHP units are combined cycles with natural gas turbines, while a gas turbine, a steam turbine and a natural gas engine are no longer in operation. The DH system is also equipped with heat storage units: 5,000 m^3 of tanks are installed in Torino Nord site, 5,000 m^3 in *Martinetto* site (near Torino Nord) and 2,500 m^3 in *Politecnico* site. The first HSS have been installed in 2005/2006. Their main purpose is the storage of the excess of CHP production at night in order to match a part of the morning peak request without the need to activate integration boilers.

Figure 1: Map of the DH network of Turin

2.2. Description of the dataset

The data used in this paper have been obtained from the monitoring system of the generation plants, and have been collected during some previous works [29, 30].

2.2.1. Available operation data

The operation data are available from October 2001 to April 2011, representing the energy consumption of ten heating seasons.The data have been collected separately for each unit of the system, i.e. CHP units, integration boilers and heat storage systems. As of April 2011, the Torino Nord site was not in operation. Therefore, the operation data considered in this paper are currently limited to the other sites. The availability of updated data could lead to an extension of the analysis, with a comparison between the old and new DH system layout. For each generation unit the thermal energy production supplied to the DH grid is available, with a time step of 6 minutes. The operation data refer to a wide-ranging period, in which the DH system has significantly evolved, both on supply side and on demand side. Considering the latter, the amount of connected buildings has almost doubled from year 2001 to year 2011, reaching almost 41 million m^3 from an initial value of about 22 million m^3. Considering the supply side, some generation units have been decommissioned, and other started their operation. In particular, the heat storage systems in *Politecnico* site have been in operation since the summer of 2006, and before 2006/2007 heating season the heat was provided only by CHP and integration boilers. In 2007 two diesel CHP engines in the Mirafiori Nord site have been decommissioned, and they are now available only for emergency operation. The CHP units in Moncalieri underwent two different refurbishments. Two CHP natural gas combined cycles have been installed, the first in 2005 as a substitution of a gas turbine unit and the second in 2009, replacing a steam turbine power plant.

In addition to DH operation dataset, some weather data have been collected. The outdoor temperature has been recorded with the same time step of the heat data, and will be used for the calculation of the energy signatures. Other weather data have been obtained with a daily time step, by aggregating different measuring stations in the city of Turin [31]. The daily data available are the minimum and maximum outdoor temperatures, the total rain, the snow level, the average wind speed and the global horizontal radiation. These data will be used to investigate possible correlations with heat consumption of the DH network.

2.2.2. Data corrections and gaps

The dataset considered in this research contains data over about 840,000 time steps. This huge amount of information had some gaps, caused by sensor failures or other database recording problems. The main part of the gaps are related to single values, but in some cases the error affects a longer period of time (up to some days in few cases, mainly in summer months).

These gaps have been repaired with value interpolations with the previous and following available data. For longer periods, a similar behavior to that of nearest days has been calculated. This approach is justified by the irrelevant number of data errors with respect to the total amount of measured data (lower than 0.1%).

The data have been collected from different data management systems, depending on the type of generation unit. The total heat supplied to the DH network has been calculated as the sum of the production from each generation unit at the same time-step.

This calculation represents the total amount of energy required by the grid at any given time, but it is not associated to a unique physical energy flow, as it is a sum of different energy flows supplied in different locations of the network.The heat load of the network considered in this study includes the network losses, as there is no information about the actual demand of the users with the required time step.

The analyses performed in this paper will take into account the "heating seasons" rather than the calendar years. Each heating season starts on October, 1st and ends on September, 30th of the following year. This choice is related to the fact that each major increase of users connections is usually performed during summer season, and the same applies to generation units refurbishment (e.g. HSS installation). As a result, considering heating seasons rather then calendar year leads to more consistent results.

Most analyses are performed using an hourly time step. Choosing narrower time steps would add little benefit thus increasing the computation time. In addition, as the goal of the paper is the description of the entire network behavior, the aggregation of 6-minute data in different locations would be affected by inertia phenomena that are much less relevant when considering hourly average values.

2.3. Analysis of heat demand drivers

The analysis of the DH network load has the aim of underlying the variations of the heat demand profile of the users over the year. Two main patterns can be noticed, with different time scales and drivers:

- an hourly pattern, mainly driven by the hour of the day, and caused by the different operation settings and parameters of the users;
- a daily pattern, mainly related to outdoor temperature, that can be studied through the energy signature methodology.

As a result, two different analyses need to be performed in order to study in detail these two aspects.

2.3.1. Analysis of hours: Heat load patterns

The heat demand variations over the day are strongly related to the different operation parameters set by the users and by the heating system manager. The analysis of the heat load profiles of the network shows the aggregation of several buildings with different behaviors but causing an aggregated heat demand that has specific features. The heat load variation over the day has also consequences on the supply side, as the operation of the generation units need to be organized in order to optimize the energy conversion in each different demand condition of the grid.

For this reason, the heat load variation over the day has been investigated, in order to find recurrent patterns ad analyze the weight of the hour of operation over the aggregated heat load demand on the network.

2.3.2. Analysis of temperature: Energy signature

The main driver for daily heat demand is related to outdoor weather conditions, which are the primary cause of heat demand in buildings. Other heat uses (e.g. domestic hot water) are usually a lower part of the overall demand of the DH system. In particular, in the proposed case study only a marginal part of the heat is used for other purposes than space heating.

An analysis of the possible weather drivers has pointed out that the outdoor temperature is the best predictor for the heat demand. The "energy signature" methodology is often used in the buildings sector, adopting a linear model to estimate the heat consumption from average outdoor temperatures.

In this paper the energy signature will be performed on a daily time step during the winter months, in order to avoid the overlook of the infra-day variations described in the previous section. An hourly energy signature will also be defined, but with the aim of highlighting different operation patterns rather than obtaining reliable values for a preliminary estimation of heat demand.

3. Results and discussion

3.1. District Heating operation summary

The heat supply of the DH system shows an evolution over the years, as the volume of buildings connected to the system is increasing (see Figure 2). Some oscillations related to average annual weather conditions can be noticed, while the heat demand distribution over the months remains comparable.

The Figure 3 shows the share of different production units in the supply side, highlighting the main contribution of CHP systems over the year. This aspect is crucial

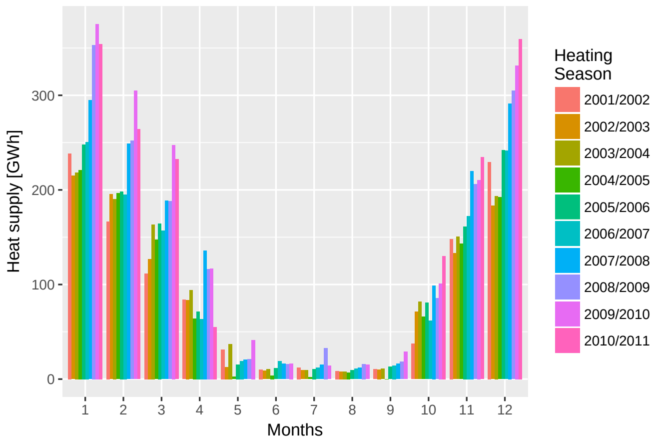

Figure 2: Monthly energy production for each Heating Season.[1]

for the overall optimization of the DH system operation, as the use of heat from CHP means a higher conversion efficiency. Moreover, in order to further increase this share, from the 2006/2007 heating season some heat storage systems have been installed. Their purpose is the operation in day/night cycles, in order to recover the excess heat available from CHP at night and use it during the day to limit the need of integration boilers. This trend is going to increase further in the following years (for which detailed data are not available) thanks to the installation of additional heat storage systems, leading to a CHP share (including HSS) of 96% in 2014[28].

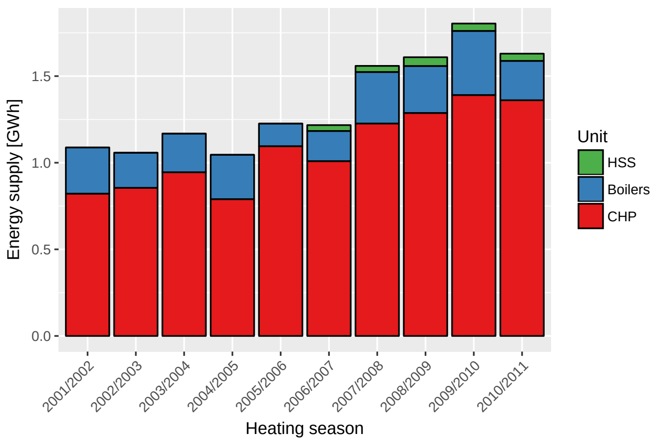

Figure 3: Annual Energy production.[1]

3.2. Hour-driven demand: heat load profiles during the day

The effect of the hours on heat demand can be described by analyzing in detail the profile patterns of each day. As an example, all the profiles of 2009/2010 heating season are reported in Figure 4.

[1]The heating season 2010/2011 is limited to April 2011, as summer data were not available.

Some common patterns over the months can be highlighted in the picture:

- The energy consumption during the night falls to low levels, due to the setback temperature control;
- The first hours of the morning (5 to 7 am) show a considerable peak, needed to warm the building up to the required set point temperature;
- During the day the trend is more constant, with two small decreases and consequent peaks, generally around 10 am and 2pm;
- Depending on the month, the height of the load is changing but the patterns are quite similar.

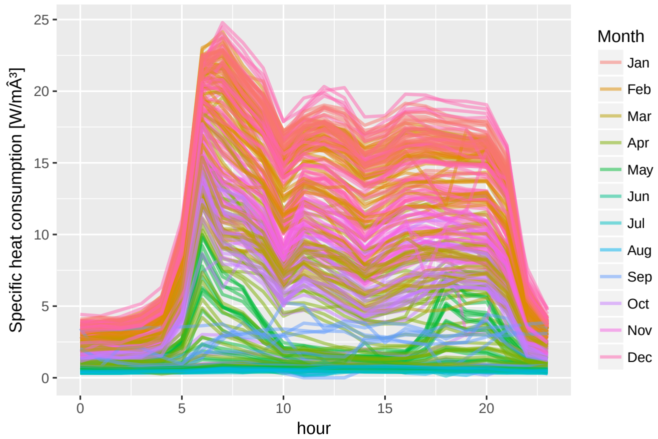

Figure 4: Daily heat load profiles for 2009/2010 heating season.

These patterns are caused by operation logics of the heating systems of the buildings, which are related to users behavior, local heating regulations, etc. Therefore, the DH demand during the day is mainly related to the users control logics, to be matched with the available generation units of the DH system.

Considering average patterns, Figure 5 shows the DH operation from 2007/2008 heating season for some representative months. The main share of the heat is provided by CHP units, as already stated by annual balances. However, at night CHP units present a potential excess of available heat that is used to load the heat storage systems that will help matching the morning peak supply. The remaining heat share, especially in winter months, is provided by integration boilers. The heat storage systems are also operated for small infra-day load/unload cycles, in order to smooth the load changes required to CHP units.

It is clear that the operational choices on the supply side have been taken to maximize the CHP share in order to match the DH network load. Other alternatives could be considered with different profiles, namely with a strong decrease of the morning peak the heat storage would probably not be required. However, such decrease would require a widespread demand side management, by starting earlier in the morning the heat supply and through slower heat ramps.

The mid-seasons behavior is similar to the winter one, but with lower energy consumption. In Figure 3 the average profile of March has been chosen, which is similar to other months in spring or autumn. The summer shows a constant low profile, the network being active only for domestic hot water production and some particular users (e.g. hospitals, distributed absorption chillers.)

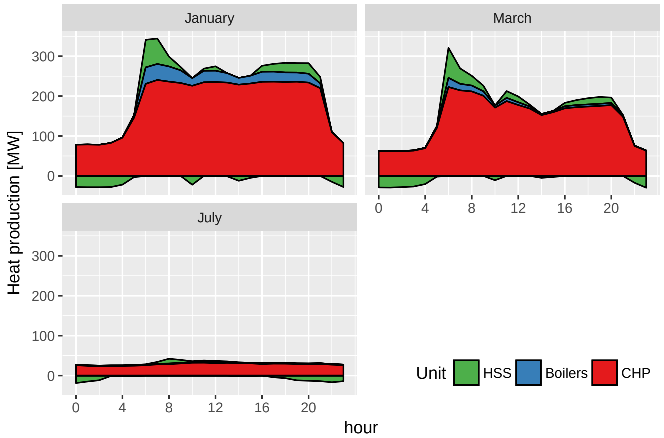

Figure 5: Average heat load for some months (heating seasons from 2007/2008 to 2010/2011).

An analysis of the network behavior can provide useful insights related to the consumption patterns of the users. The network heat losses are a minor part of the energy involved, especially during the heating season. Moreover, the heat losses have a slight variation w.r.t. time, as the network temperature and the ground temperature have generally minor variations.

3.3. *Temperature-driven demand: daily energy signature*

The effect of outdoor temperature on heat demand can be described by using the energy signature methodology (see section 2.3.2).

Daily data provide a good example of the usefulness of energy signature for the description of the energy performance of heated buildings. The use of this method on a DH network can be performed considering the network as an aggregation of single buildings with comparable consumption patterns.

The daily signature of the entire DH network is plotted in Figure 6, considering the winter months only (from November to March), over all the years available in the dataset. The adoption of specific energy as variable is needed in order to compare different volumes of buildings connected to the network. There is some point scattering, although R^2 has an acceptable value. The colors in the plot highlight the different heating seasons considered for the chart.

A further investigation can be performed by drawing the energy signatures for each heating season. The single

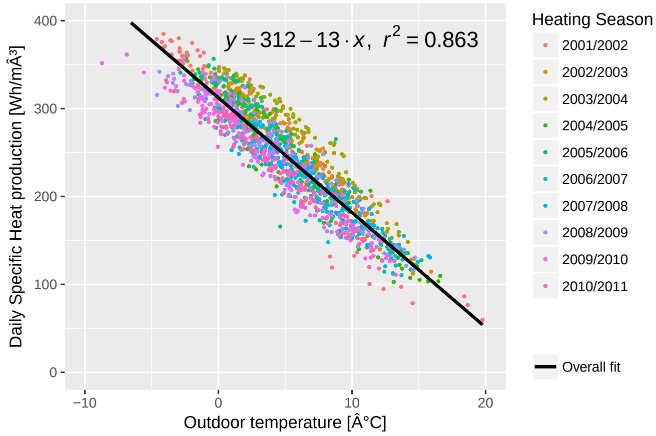

Figure 6: Daily energy signature of the network during winter months (Nov-Mar).

signatures are plotted together in Figure 7, with the global signature as reference. The equations for each season have been reported in Table 1, together with the total volume of the buildings connected to the network.

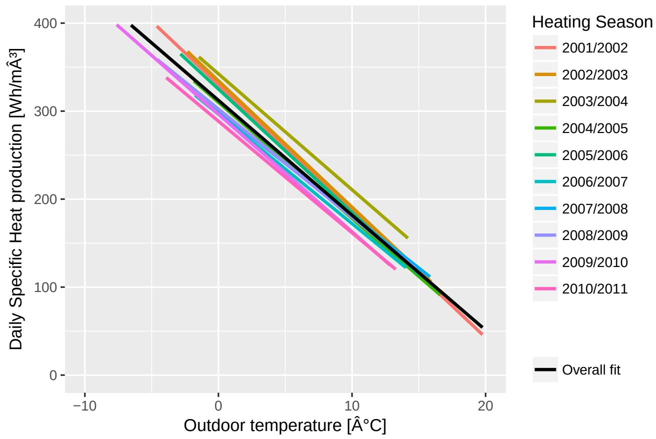

Figure 7: Daily energy signature of the network during winter months (Nov-Mar), calculated for each Heating Season.

The trend suggests a generalized decrease of the energy consumption. However, there are a number of aspects that can affect the energy performance over the years, as in ten years of operation multiple factors can have an impact on these analyses. The following aspects are worth mentioning, considering DH operation:

- The increase of buildings volume connected to DH network causes a different distribution of buildings features and operational parameters;
- The connection of new areas will then modify also the network topology, and therefore the network losses could be affected in different ways depending on the pipes length and diameters, the network temperatures, water velocity, etc.;

Table 1: Daily energy signatures parameters

Heating Season	Heated Volume $[Mm^3]$	Intercept	Slope	R^2
2001/2002	22.51	330.20	-14.38	0.929
2002/2003	23.08	334.44	-14.36	0.940
2003/2004	22.83	342.34	-13.17	0.884
2004/2005	24.54	309.98	-13.18	0.926
2005/2006	24.59	325.05	-14.03	0.928
2006/2007	31.89	296.44	-12.42	0.858
2007/2008	36.13	300.15	-11.90	0.886
2008/2009	36.42	302.36	-12.28	0.919
2009/2010	38.61	296.51	-13.35	0.921
2010/2011	40.98	288.53	-12.68	0.946

- The installation of new heat generators and the decommissioning of others can lead to slightly different operation logics, resulting in some shifting of energy consumption over the day. However, daily analyses should not be much affected.

Finally, it has to be stated that in this specific application the linearization of heat consumption w.r.t. outdoor temperature is affected by some approximations:

- The outdoor temperature considered in this study is a single value for a wide area. Some local phenomena could cause some degrees of difference over the city (e.g. presence of green areas, rivers, etc.);
- There is no information about the internal temperature of the heated buildings: a physic linear dependence connects heat consumption with temperature difference. However, if the internal temperature has some fluctuations, or differences among buildings, the calculation of energy signature can significantly be affected;
- Each measure of heat flow can be affected by some errors, and the same effect can be noticed on outdoor temperatures.

All these aspects are to some extent related to the residuals of the linear regression w.r.t. outdoor temperature. However, the use of daily energy signature seems to be an useful tool for an estimation of the expected heat consumption based solely on the outdoor temperature. An application could be related to the day-to-day prediction of future heat needs based on the available weather forecasts.

3.4. Hours and Temperature: hourly energy signature

While a daily energy signature can provide a tool for a rough linearization of energy consumption versus outdoor temperature, hourly energy signature has usually too much point scattering to provide reliable numbers. However, some interesting trends can be observed in order to evaluate the different behaviors over the hours of the day.

Figure 8 shows an hourly energy signature of the whole network in winter months (November to March). The plot shows two different patterns during the day and during the night, due to the night setback temperature control or the system switch-off, depending on the building. The "transient" hours are located outside of the two main groups, resulting from the average of the two main behavious (gray points in Figure 6). Moreover, the green-colored area at the top of the daily cloud represents the morning peak needed to heat up the buildings.

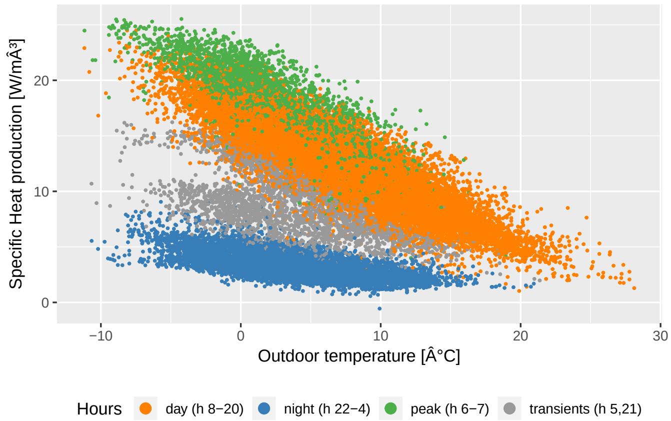

Figure 8: Hourly energy signature of the network during winter months (Nov-Mar).

Some further qualitative considerations can be deduced from Figure 8. Different operation logics (e.g. with no or lower night temperature setback) would cause a collapse of the "night" and "peak" behaviors over the "day" behavior. This variation could lead to an increase of the overall energy consumption, but could lead also to a number of advantages, such as:

- a decrease of the peak power request in the network;
- the possibility of lowering the operation temperatures of the heating systems of the buildings, as the maximum heat required would be much lower;
- a general lower operation temperature of the network, which could help to integrate renewable sources (e.g. heat pumps, solar) in the supply side of the DH and lead in some cases to better conversion efficiencies.

These considerations could be the basis for further analyses, which would require some additional information on the features of the buildings and the operating temperatures of the network.

3.5. DH operation in summer

The analysis of the network in summer months gives some insights on the average heat demand of the city.

Figure 9 shows the distribution density of the daily specific heat during summer months for each year available. The months that have been considered for the analysis are June, July and August, as May and September have several outliers that causes anomalies. Year 2005 shows a clear anomaly, as for a part of the summer the network has been shut down for major maintenance activities (including heat storage systems connection). The other years have similar distributions, the average being around 13.0 $Wh/m^3/day$, with some higher values related to particular weather conditions. The average heat consumption during summer is roughly representative of the share of heat losses of the network and the domestic hot water consumption. Also heat losses are at some extent related to buildings total volume, as the increase of connections usually requires additional pipes.

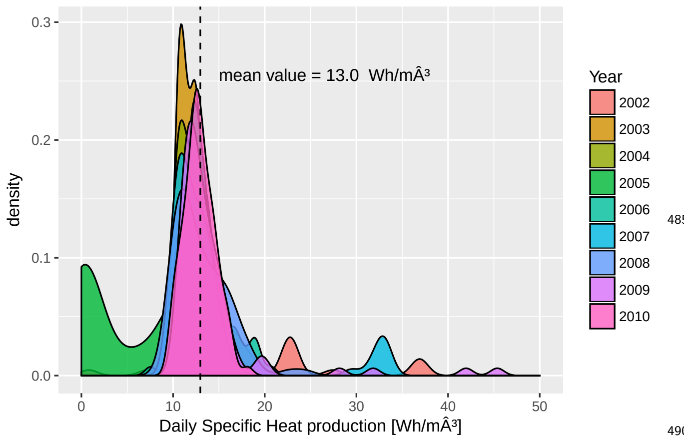

Figure 9: Summer months: Distribution density of Daily Specific Heat (Jun-Aug).

4. Conclusions

The aim of this paper is to analyze the operation of a large DH system over several heating seasons, in order to find insights about the main drivers of heat demand profiles.

The analysis of the entire network does not allow considering the features of the connected buildings; on the other hand it has been noticed that even with a significant increase of the volume of buildings connected to the system, the results do not show significant differences. The main drivers of the heat consumption have been found to be the different operation settings during the day (i.e. the night temperature setback or night shut-down) and the outdoor temperature.

The daily energy signature calculated for different years considering specific heat demand shows similar behaviors, with some differences that could be related to the network layout changes and the average characteristics of the buildings connected to the network for each year.

The use of energy signatures with an hourly time step provides less useful numerical results, but it allows highlighting the different behaviors related to normal daytime operation, night-time operation with temperature setback, morning peak operation and transient hours.

This last analysis suggests that the night temperature setback has significant consequences on the heat demand, causing a strong energy peak in the morning. The change of this operation logic could lead to a decrease of the maximum heat demand of the buildings, resulting in the possibility of lowering the network temperatures and enhancing the integration of alternative energy sources (e.g. heat pumps, solar), and in some cases increasing the conversion efficiency. However such analysis should also consider the features of the buildings, and should be performed on a subset of the network with more detailed operation data, especially on the parameters of the heating systems of each building.

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