Demand response and other demand side management techniques for district heating: A review

Demand Response and other Demand Side Management techniques for District Heating: a review

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Abstract. *If demand side management in electricity grid is a well known concept, the application to district heating systems (i.e. modifying the thermal demand in order to make it more compliant with the heat production) is significantly less widespread. Various attempts can be found in the literature concerning thermal demand modification in district heating, despite often researchers working on this topic are not fully aware of the other research activities also because various names are used to identify similar techniques. This paper represents the first survey on the use demand side application in district heating networks. The review clarifies the terminology and the stages for implementing demand side management to district heating network. Simulations and real applications are both considered in the review, including direct and indirect demand side management (demand response) . Demand side management is found to be a great technique for district heating management. Various works show that the following benefits can be achieved: peak shaving up to 30%, doubled load factor, reduction of primary energy needs up to 5%, emission and cost reduction up to 10%. This clearly leads to significant cost and emission reduction, contributing to the decarbonization of urban areas.*

keywords

Demand response, load shifting, thermal load management, demand modification, peak reduction, district heating network management.

1. Introduction

District heating (DH) system is a largely widespread technology which allows overcoming the adoption of inefficient individual devices for space heating and domestic hot water production in buildings [1,2] . Currently, the trend is exploiting more and more low-grade energy from cogeneration plants [3] and industrial sites [4], along with renewable energy sources [5]. Heat-only-boilers are increasingly abandoned due to low exergy efficiency, except for covering peak loads. Despite the potentially large efficiency of DHS, there are various sources of inefficiencies: a) thermal losses along pipelines and in substations [6] b) use of unnecessary high quality energy for low temperature purposes [7,8] c) unnecessary pumping costs [9] d) presence of bottlenecks limiting additional connections [10,11]. An attempt to reduce effects of inefficiency consists in managing the generation side [12]. The gap between demand and production plays a fundamental role to increase the impact of the inefficiency sources. Indeed, when undesired high thermal request occurs, technologies with low efficiency, usually Heat-only-boilers, must be used [13]. Furthermore, flexibility of the electricity production in cogeneration plants decreases when large thermal loads must be covered [14, 15]. Additionally, peak loads cause high mass flow rates circulating within the pipelines with consequent bottlenecks (or congestion), limiting future expansion of the network, with connections of new-end users, and increasing the pumping costs. Differences between demand and production can arise because time or space gaps due to a) distance between production and consumption sites and b) time difference between the production and consumption. Both the gaps create a time discrepancy at plant level.

A most common way to address this gap consists in the use of Heat-only-boilers, that are usually adopted to fill the peak demand. Alternatively, thermal storage can be used. This usually consists in the use of large tanks which exploit the sensible heat of water. These are installed near the thermal plants or in strategic areas of the city. Storages are charged when a production surplus is available (or when cost of thermal energy is low) and discharged when the demand exceeds production capacity of the main plants (or the thermal energy cost is high). Storage installation in DH and cooling systems is very common, as shown in [16]. Various papers in the literature show the advantages of using storages connected to DH [17–19]. Possible issues are related with the investment cost but also the lack of free land for the installation (that is expensive and not easy to be found in urban areas where DH are located). However design and operations are quite easy and this does not require specific software for its management. Another option for reducing gaps between demand and production consists in modifying the demand of the end-users. This allows avoiding problems related to thermal storage installation. This option is mainly called Demand Side Management (DSM) if all the techniques for demand modifications are considered, or Demand Response (DR) if only a subset of options is considered (in particular not definitive actions on the buildings). These terms have already been widely used for electricity management [20, 21]. Modification of the demand is actually not straightforward for various reasons. At first, the main goal of DH is *"maintain a suitable indoor climate in the connected buildings and not to supply heat [22]"*, therefore comfort indoor quality should be ensured when modifications of the thermal demand profiles are implemented. Secondly, the large thermal capacity of the network makes the sum of the demand in the buildings different that the thermal load at the plant, because of the thermal transient and the large distances between end-users and plants [23]. This means that proper network simulator should be used (especially in case of large networks with large temperature differences) to achieve the best thermal request at the power plants. The third is that building thermal request over time should be known in advance in order to properly modify it. Furthermore, to achieve benefits from DSM the actions done in each buildings should be properly combined, since all of them affect the total thermal demand profile.

The main problem, up to now is that researchers dealing with DSM in DH often do not know progress done in this field from the other researchers. Various scientific papers in the literature states that few works on DSM in DH exists [24–27]. This is not completely true, but it should be considered that DSM in DH is often called in different ways. Actually various simulations and experimental tests, on single buildings or groups of buildings have been performed.

This paper represents the first review paper on demand side management in district heating systems targeting at being a complete introduction to the subject. The paper aims at reviewing the existing literature on indirect and direct demand side management, considering the various steps that is necessary to follow for properly implementing the demand side actions. Both experimental tests and simulations are analyzed in the survey, including works on the storage capacity of the buildings. The paper provides the reasons for implementing DSM in district heating networks and the benefits that can be achieved. The paper is structure as follows:

1. Terminology about DSM is discussed in Section 2 since this is the main cause of the difficulty of paper related to the same topic
2. Various types of storage in DH networks are discussed and the reasons making DSM in DH an interesting option are reported in Section 3;
3. Typical requirements and modeling structure to implement DSM are discussed in Section 4, considering how problems are tackled in the literature;
4. Application of demand side are discussed along with the results obtained in Section 5.

A careful literature review has shown that many attempts and progresses have been done in this field in the last years. Although results are sometimes controversial, the globally outcomes is that DSM can provided significant peak shaving and not negligible reduction of cost and primary energy consumption.

2. Terminology for DSM

The terminology can be considered one reason that makes the literature review on DSM a critical issue. *Demand side management* is probably the most diffuse term used to describe the modification of the user demand in order to meet some requirements or reach specific goals. Demand side management includes all the measures acting at demand level, aimed at reducing the consumption/costs/emissions or increasing the income from the energy sales, including the methods to improve energy efficiency of the buildings (e.g. retrofitting measures). Another very diffuse name is *demand response*. Concerning demand response, this is a subset of demand side management, only including the non-permanent actions done on the demand.

Both the names are born in the electricity field [28, 29]. In this sector, the aim is modifying the electricity loads of the final users such that the overall demand is more convenient for the supply side. As concern DSM in district heating, the aim is modifying the portion of the building thermal demand (for space heating and/or domestic hot water) that is supplied by district heating in order to change the overall DH network thermal load. This allows changing the characteristics of the overall load profile to make it compliant with the production side (i.e. combined heat and power plants, heat only boilers, geothermal and solar plants, heat recovery systems, etc). Most of the works on DSM are related to electricity. The adoption of the same terminology for the electrical and thermal networks makes the literature search for DSM in thermal networks quite complicated.

In order to include the contribution of a different energy vector (i.e. heat), an attempt has been done in [24], where the expression *thermal load management* has been used. This expression is used to include the demand side management, aimed at modifying the thermal load, related to both heat and electricity energy vectors.

Various works in the literature, generically call it *variation or modification of the user demand*. Another option consists in calling it *virtual storage* [30]. This is done in the cases the building envelope is used to achieve the same effects of an energy storage. The modification of thermal request is called *load shifting*, in case the heating system schedules are shifted in time; this approach can also be called *heating system rescheduling*. Furthermore in various works the actions are called *load shedding* [31], *load control* [31], *load management* [22, 32] to indicate a generic management of the load side.

This review is performed adopting Science Direct and Google Scholar repositories. Starting from the cross-referencing of simple keywords (e.g. *demand response*, *demand side management*, *district heating*, *thermal load*, *load shifting*, *load modification*), the reference of the first results are analyzed to find other related works. False-positive results related to electric field can be avoided by defining the presence of the keyword *district heating* in the searched manuscripts. To avoid misleading the papers on this topic in the future should include in the title (or at least keywords and abstract) *demand side management* or *demand response* and *district heating* or *thermal networks* or *thermal load*.

3. Why DSM in district heating networks

In DH systems there are various ways to meet demand and production. All of them consists in storing a fraction of the energy produced, in order to make it available at a different time. There are mainly three ways for acting on discrepancies between demand and supply, which correspond to three masses that can be exploited to store heat:

1. *Proper heat buffer (thermal energy storage system)* installed near the plants or in strategic areas of the network. These are charged when an extra production is available (and convenient) and discharged in the case of load peaks or supply valleys. These are widely used worldwide [33–35]. The main disadvantages of using thermal storage to reduce gap between demand and production are the followings:
    - A dedicated space has to be available for the installation. This is a typical problem of all the storages, at various levels (distributed, concentrated [36]) and for all the purposes. However in the case of district heating, that is usually adopted in densely populated areas (space availability limited and land costs high) the issue can be significant.
    - Non-negligible costs for the installation. Cost is lower in the case of water, that is used there are no constraints about the storage volume. The cost increases in case of latent heat storage, used in case of constraint on space availability, due to their large energy density [37].
    - Thermal losses from the storage towards the environment and the not perfect mixing constitute a further energy loss in the system [38].
    - Problems may arise in case of design and approval stages because of connection planning and, in some cases, the lack of suitable supportive legislation [39].

   Despite these disadvantages, water tanks are widespread because of the large flexibility offered and ease of management.
2. *Exploiting the water mass within the network pipelines as a storage.* This can be done by acting on mass flow rate or supply temperature [40, 41] for exploiting the network thermal capacity as a storage [42]. Management of this kind of storage is more complex since the storing time strongly depends on a) network topology b) pipeline diameter and length c) demand evolution of the buildings. For these reasons, models simulating the network thermal dynamic are required to achieve

precise goals. In Denmark, Lund [43] estimated that the total network capacity as storage is about 5 GWh, considering a total load of 115 GWh and a temperature difference of 10 K. This is about 10% of the storage capacity installed in Denmark.

3. *Exploiting the building envelope as a storage.* This is done providing heat at a different time than that is required, increasing the temperature of the indoor ambient and the envelope [44]. This can be done since the thermal capacity of the building, as shown in [45] is usually significant for the thermal balance. Because of the wide range of building types (volume, geometry, construction material, insulation, etc) this is not a straightforward task. Numerical tests performed in [46, 47] show that the available heat power that can be stored in buildings is between 9 to 54 MW depending on the size and the envelope characteristics, when considering an induced variation of the outdoor temperature (for regulation purposes) up to 6 °C.

In this framework, DSM consists in modifying the thermal request profile of a building. This allows exploiting as a storage both the building and the part of network connecting the building and the pipeline. Romanchenko et al. [48] compared the use of a building as a storage with the use of a storage tank. Results show that storage tanks can store more than double the amount of heat, because of their ability to store energy also on the medium-term. However, in case of DH systems, several buildings are available as thermal storages and they can be operated individually in different ways. It is clear that operating differently individual building is a core option for DSM application. A comparison reported in [41] shows that the contribution that network pipelines can give as thermal storage is limited when compared to the building envelope. The use of the building envelope as a storage requires the involvement of the customer (among the stakeholders) since a modification in the indoor conditions, although small, occurs. As a conclusion, DSM offers a potential of storing energy alternative to the classical water tanks and easier to control than the sole exploitation of pipelines, that does not need high investment costs but a careful planning and a wise decision intelligence.

Various benefits in the application of DSM to DH systems are shown in Fig. 1. DSM allows a smarter management of the supply side since allows matching production and consumption evolution. This leads to a smarter exploitation of the available technologies. The benefits that can be obtained are both economical and environmental since both larger income from selling electricity or heat pumps adoption [49] and a highest rate of waste heat and renewable energy [50] can be achieved. Concerning this specific aim, in [51] the peak heating demand is shown to be reduced by 50%, if the thermal inertia of the buildings is properly used as a buffer to increase renewable energy penetration. Since DSM may allows the flatttening profiles flatter during the entire working life of the DH system, new DH can be designed in a smarter way: pipelines installed can be smaller, cogeneration capacity can be reduced and installation of Heat-only-boilers is no more necessary. In operations, use of DSM allows reducing occurrence of bottlenecks, as the mass flow along the pipelines is reduced. This leads to three main consequence: a) the possibility of connecting extra building without adding new pipelines b) the reduction of pumping power c) an easier management of malfunctions e.g. pumps failure, leakages, pipeline breakups, problems in power plants. Furthermore moving towards multi-energy systems [52, 53], DSM can be adopted to integrated energy systems including different energy vectors, to increase the overall flexibility; for the details on this topic refer to [54, 55].

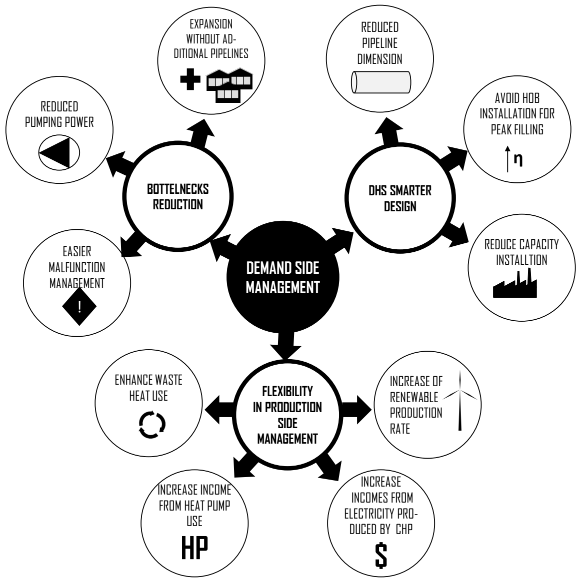

Figure 1. Effects of DSM applications to DHSs

Fig. 2 shows, by way of an example, typical effects on the thermal demand that can be achieve by adoption of DSM. Fig. 2a shows the effects of the change of the control strategy on the thermal demand of buildings. In particular, the thermal demand of two buildings is reported without and with the application of DSM (in particular change in the control strategy). The adoption of the demand side management allows a significant reduction in the peak demand. Fig. 2b depicts the effects of the DSM (in particular building heating system rescheduling) on the overall demand of a distribution network. The network thermal demand in case of DSM is much flatter than the other case (about 30% of the peak demand reduction).

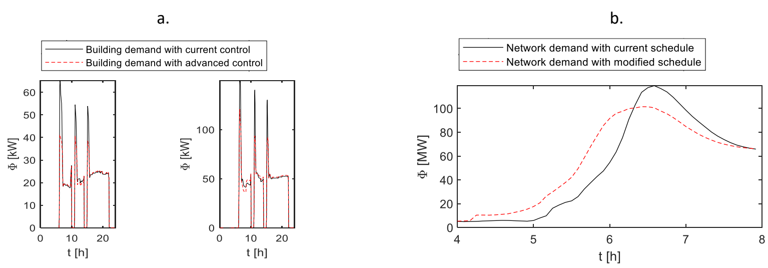

Figure 2. Effects of demand side management a) building thermal demand with and without an advanced substation control strategy b) network demand obtained with and without schedule shifting of the heating system

4. How implementing DSM in DHS

There are three main actions that can be performed to achieve modifications of the building thermal demand profiles.

Retrofitting measures. The first action concerns the retrofitting of connected buildings. This action modifies permanently the thermal request of a building (energy cut over 45% by pursuing deeper retrofit measures can be achieved [56]). This is a DSM but not a demand response action since this leads to a new permanent thermal request. However, the new request can reduce the gaps between demand and production and the mass flow rates flowing the pipelines. Retrofitting measures is a very interesting option when the goal is to connect further buildings to the network without pipeline/topology modifications. Retrofitting can also enhance benefits from other DSM actions, since it can make building envelopes more suitable for application of direct or indirect DSM [57].

Indirect DSM. The second method consists in using different tariffs for different time of the day, the so-called indirect DSM. This has been largely used in electricity market and attempts are done also for thermal energy selling [58]. This technique does not requires implementation of any control system to manage the demand making it easy to be implemented. Also, investment costs for indirect DSM are negligible. An analysis of the effects of changes on the tariffs (and as a consequence on the profiles) should be addressed before proposing new tariff schedule. The main issue is that indirect DSM can produce outcomes with a high level of uncertainty. Estimation of user response in tariff changes is difficultly predictable: it could also lead to the creation of peaks that are just shifted in time, as shown in [59]. This risk should be carefully taken into account during the preliminary analysis. An option to achieve more satisfying results is to proceed by steps of adjustment. In fact, in case the implementation of Indirect DSM does not lead to the planned target, values and schedule of the tariffs can be readjusted. In this framework, and interesting analysis is reported in [60]; this work proposes tariffs in order to push end-users to modify their thermal request by shifting it ahead early in the morning or at night. This option may be further explored taking advantage of the digital technologies.

Direct DSM. The third option is the direct load control; in this case, the demand profiles are directly managed in order to make it as similar as possible at the optimal profile. This can be done in two main ways: 1) by modifying the on/off schedule (i.e. time the building heating systems are switched-on/off) or the attenuation schedules 2) by adopting a different regulation strategy. Furthermore this can be applied a) just in some selected buildings or b) in all the buildings. Direct DSM allows modifying the thermal load in a much more refined way, depending on the effects that want to be achieved. The approach can rely on optimization processes, real time analysis or daily-ahead analysis. Direct DSM makes easier to address goals, since the effects are easier to be controlled. This is especially true in the case the thermal load evolution at plants strongly change in time. On the other hand, equipment for load control and development of tools for performing DSM are required and a certain budget should be allocated for equipment and research activity. However due to the increasing interest in automation of building, services and platform suitable for the equipment control are currently available on the market [61].

There are various advantages and disadvantages in these options and they produce different effects. Fig. 3a reports the three actions previously discussed in term of responsibility (y axis) and DSM flexibility (x axis), i.e. the modification frequency. Direct DSM allows continuously changing the kind of actions applied (and thus the system response). Indirect DSM can be modified when different tariffs are proposed to the end-users (no more than few times a year). Retrofitting is a permanent action. As concerns responsibility, indirect DSM, allows avoiding problems related to the quality of service offered to the individual buildings, since the selection of the schedule is done by the end-users. In case of direct DSM, usually the company takes the service quality in charge. This means that the effects of load modification should be quantified by proper tools or experimental apparatuses with the aim of keeping indoor conditions within comfort levels. Direct DSM is definitely the most widespread in the literature since it allows reaching the goals in more controllable ways. For this reason, the review paper is mainly focused on the Direct DSM, taking into account the input and the analysis that should be considered to achieve smart DSM. In particular, concerning Direct DSM this can be performed with different time gaps between the decision and the application. The two most widespread are the day-ahead DSM and the real-time DSM, as reported in Fig. 3b. The first option consists in using past and forecasted data to perform the DSM in the following day. The second option consists in applying DSM to a time immediately after the decision. The two main difficulties in the selection of a proper intelligence to perform real-time DSM concerns the necessity to 1) continuously uploading data to perform real time decision 2) compute results in very low computational time 3) be able to manage different time period and not only a daily slot.

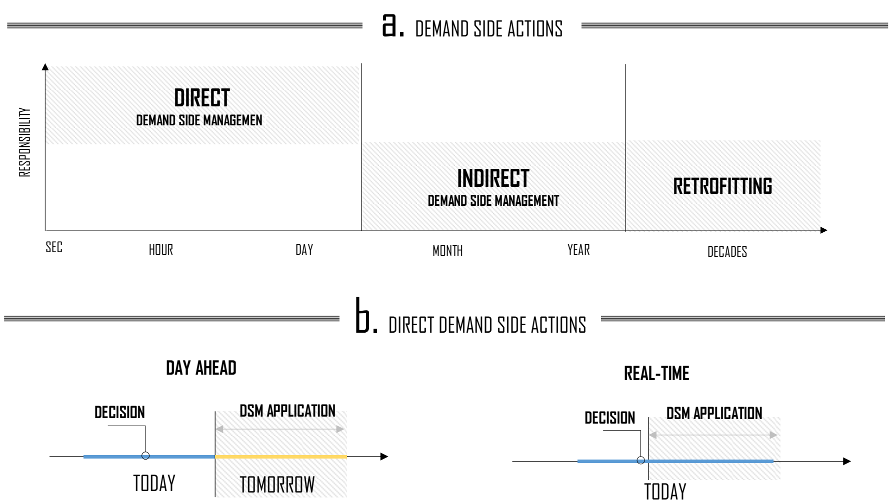

Figure 3. Basic techniques for demand side management

Fig. 4 describes the information exchanges in the application of demand response to DH; this includes the various stakeholders, the DH structure and the information fluxes between the various parts. Data gathered at substation or building level is the piece of information used to plan possible operation changes for DSM. Data are measured with time steps between 10 s to 1 h and saved in a data repository. The smaller the time step, the larger the flexibility in management that can be obtained. The intelligence relies on the data saved in the repository in order to perform DSM to address the goals selected by the energy company.

Actually, the information exchange can be much more complicated since effects of changes in demand side are affected also by other systems, as shown by the various arrows in Fig. 4. These are:

- The other users. The effect of the DSM performed on a building is not independent from the DSM performed on the other buildings connected to the networks.
- The network dynamics. The effects of DSM are strongly affected by the network dynamics, that is a consequence of the topology, the way the buildings are connected, the pipeline design and dimension.
- The location and type of the plants used, that mainly affect the goal for DSM.

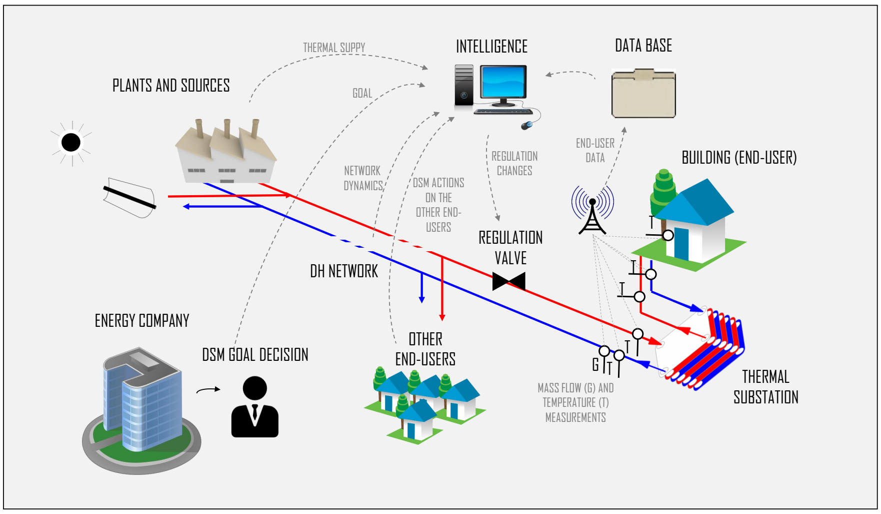

Figure 4. Conceptual schematic of DSM implementation: basic information exchange

Since DSM in DH systems is a complex matter, involving various systems, all these must be taken into account. A conceptual schematic with the aspects that should be considered for the implementation of DSM is reported in Fig. 5. The first two steps consist in:

1. the selection, through a preliminary analysis, of the quantities affecting DSM. These are the inputs to be provided to the DSM intelligence. This point is discussed in Section 4.1.
2. the selection of the goals to be achieved; various goals can be selected depending mainly on the main issues related to the specific network (e.g. bottlenecks), depending on the kind of plants feeding the network (e.g. Heat-only-boilers to cover peak loads). Goal selection is discussed in Section 4.2, taking into account the wide range of different goals related to the works available in the literature.

After the preliminary analysis, the other steps to achieve the best possible DSM are:

1. Checking the effects of the heat supply modification on the indoor conditions. This can be done in the following ways as discussed in Section 4.3.
2. Taking into account the effects of the other building modifications or the network dynamic, as discussed in Section 4.4.

3. When more than a building is subject to DSM (which is the typical situation), combined approach should be used to find the best DSM strategy including the contribution of all the buildings and the network. This is done by mean of a decision intelligence, as described in Section 4.5.
4. The intelligence decision is put into action by means of a signal sent to the regulator; this is discussed in Section 4.6.

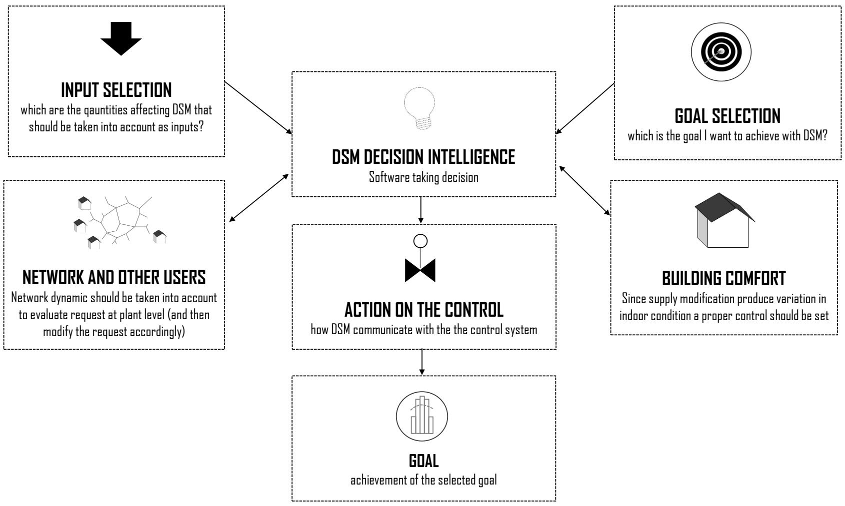

Figure 5. Basic scheme for demand side management implementation in DHS

4.1. DSM input (demand prediction)

Information required for DSM application are mainly those influencing the building demand evolution. The main ones are:

- Metereological conditions;
- Buildings characteristrics (geometry, envelope thermal capacity, transmittance, volume, etc..);
- Occupants behaviour [62];
- Other information for endogenous contribution evaluation;
- Schedule of the heating system;
- Regulation strategy of the user (e.g. climatic curve);
- Kind of thermal plants used to supply the network;
- Network and plant operation strategies;

Input data are mandatory for two main reasons:

1. The demand evolution should be estimated to properly modify it. Since the meteorological conditions of the day (and the previous day), the building characteristics and the schedule have a strong influence in the demand evolution, physical or black box models can help to a more realistic prediction.
2. The effects of DSM on the indoor comfort should be estimated. This point is deeply discussed in section 2.2.

In case of DHS, with a noteworthy number of buildings, usually it is not possible to rely on all the required data. Concerning building characteristics, often only some of them are available, such as volume and year of construction. Furthermore, occupant behaviour and details on endogenous contributions are usually unknown. These issues, along with the significant computational costs required, make it impossible an accurate modelling of the dynamics of all the buildings connected to the network by means of the specific software (like Energy Plus [63], DOE-2 [64], eQUEST [65], ESP-r [66]). For this reason, the demand of buildings connected to DH systems is usually estimated by means of black box approaches [67] or simple physical replaceapproachesmodels. As shown in [68] it is possible to evaluate the demand evolution for the buildings in DH by using data measured by the equipment installed in the substations (i.e. the same data used for billing purposes). This technique allows the automatic creation of the model for the thermal load forecast in all the buildings connected to the network. In case this way is not viable, an option consists in analyzing a limited number of buildings and then, through a clustering approach, estimating the thermal request of all the others, as shown in [69]. Clustering can be done by referring to various characteristics such are years of construction, type, volumes etc.

Independently by the approach adopted, the substation data should be gathered at a time resolution sufficiently fine. The specific limit mainly depends on the temporal scale of DSM action. When DSM is used to manage the daily demand evolution, the time step should be at least 30 min and better with a smaller time step (e.g. 5 min). In case the goal of DSM is the cost reduction, an important piece of information concerns the evolution of energy prices. This also can be estimated relying on historical data related to costs, thermal consumption, and weather.

A major problem in the adoption of data for creating/training models for load prediction is the management of large amount of data. In the electric field, demand response has been analyzed along with big data analytic [70, 71]. As concern district heating, data are mainly: a) the building characteristics and b) the time evolution of consumption, temperature, mass flow rates, etc. In case of large networks, up to some tens of thousands substations must be managed. The developed platform must be linked to all the substations for data exchange. Data exchange should guarantee substation data gathering and possibility of changing the substation regulation details (e.g. schedule), after the elaboration of suitable mathematical models. These data can be managed with proper platform. An intelligent system for DSM application is developed in [72] through a dedicated ontology (web ontology language) along with semantic rules suitable for handling heterogeneous data sources. An Internet-of-Things software infrastructure is proposed in [73] for simulating new control policies in near real-time in a city district.

From a wider point of view, in case more than a building is subject to DSM (as usually occurs) application of DSM on a building depends on the strategy applied to all the other buildings. However, this cannot be considered as an input since a mutual dependence occurs between DSM applied in the various buildings; for this reason combined strategy are used to effectively achieve the goals, as shown in Section 4.2.

4.2. DSM goal selection

Various goals can be achieved by DSM in DHS, as discussed in Section 3. A generic goal can be considered as “to change the request in order to make this more profitable for the considered system at a certain time"; this usually consists in making it as similar as possible to a certain ideal evolution. The process to reach this ideal evolution is complex because of the following factors:

- Uncertainty on the demand that will occur the time DSM will be applied.
- Uncertainty on the production from renewables and on the amount of waste heat available [74].
- Unpredictability of the heat cost evolution (if any).
- Possibility of occurrence of malfunction.
- Possible presence of substations in transitional sub-optimal conditions (e.g. fouling deposition.)
- Difficulty of predicting the thermal profiles at the power plants given the costumer thermal request.

For these reasons, the goal selected for the DSM is usually different than the perfect matching of two unknown curves, affected by various uncertainties. Some possible goals (also schematized in Fig. 6) can be:

- Reduction of thermal peak, as done in [60, 75];
- Keeping production below threshold values (defined through a previous analysis) that should not be exceeded, as in [76];
- Diminishing primary energy consumption, as in [77];
- Minimizing the cost for thermal energy, as in [25];
- Best integration of renewable sources, as in [50, 51];
- Minimization of the energy produced with a unfavourable technology (such as Heat-only-boilers) [78];
- Maximization of the profits, as in [49, 79, 80];
- Reduction of the supply temperature [81];
- Reduction of the load variation, as in [31, 47], or similarly, minimization of the load factor, defined as in Eq.1 [82], where Φ is the thermal load of the entire system:

$$\gamma = \frac{\Phi_{average}}{\Phi_{max}} \tag{1}$$

In some cases a combination of the goals has been used to define the objective function [83]. The goal selection is crucial in order to achieve a proper effect. In [78] it is shown that the selection of the objective function is an important aspect for DSM. In fact, it is shown that in some cases, that when the DSM has the goal of reducing maximum peak value (-2% achieved), the primary energy consumption does not decrease significantly (-0.35%). On the other hand, when the minimization of Heat-only-boiler production is selected as objecting function (-0.8%primary energy), it is possible that the maximum value of the thermal peak even increases (+0.5% in the considered case). The contemporary application of DSM to electricity and district heating can be done [84]. As shown in [50] this approach can be use in order to facilitate the wind power integration for energy conservation in a framework including electrical grid, heat pumps and district heating; this is shown to allows reducing the consumption of fossil fuel. In a context of DH temperature reduction, in [81] a methodology for assessing the local temperature reduction potential in district heating networks by DSM through thermal retrofitting is shown. A specific analysis on the Klagenfurt network (in Austria) show that a reduction of 1.2 K (temperature) and as a consequence 21 MWh (thermal losses) can be achieved.

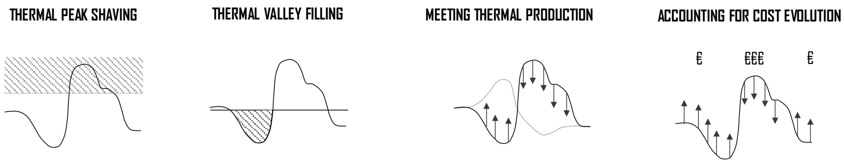

Figure 6. Specific goals for demand side management implementation in DHS

4.3. Accounting for building indoor comfort

Modifications of the demand profiles leads to changes in the indoor conditions. For this reason, DSM attempts are usually done taking care of indoor temperature evolution. The aim of DSM is to modify the thermal load as long as the end-users do not notice differences in the comfort perception, with respect to the previous settings. In the works found in the literature, this is done in different ways.

A widely used approach consists in the evaluation of the building time constant, τ. This is the ratio between the energy that can be stored in the building and the thermal power to keep the indoor temperature constant. The time constant is proportional to the thermal capacity and inversely proportional to the heat transfer coefficient. Considering a building in setback, the characteristic time affects the temperature decay as expressed in Eq.2:

$$T(t) = T_0 + (T_1 - T_0)e^{\frac{-t}{\tau}} \tag{2}$$

τ can be used as a reference quantity to measure the response of a building when DSM is performed. Considering for simplicity a building as a thermal storage, thermal losses and thermal conductivity affect the DSM as expressed in Fig. 7. When the building thermal capacity is large the potential for storing heat is high, while when thermal conductivity is high the losses of the storage are significant. Indeed, when time constant τ is large, thermal losses are small or thermal capacity is large, thus use of the building as a storage is interesting since lots of heat can be stored with low thermal losses. On the other hand, when τ is low is because the building is not suitable for DSM application since thermal losses are high and heat storage capacity low. Another factor strongly influence the DSM applicability is related with the medium (indoor air) between DH water fluid and the storage media (envelope). In fact, much insulated buildings fast overheat indoor air when subjected to an extra heat. This is because of the lower heat transfer between the indoor air and the envelope. In case of low thermal conductivity buildings, it is easier to "charge" the building envelope with the excess heat, although an higher fraction is lost.

This limitation can be reduced by installation of a phase change material in the building envelope, as discussed in various works [85]. This enhance the heat exchange between indoor air and envelope, in case of well insulated buildings. In [86,87] it has been demonstrated that a significant load shifting potential exists in well-insulated buildings without compromising the indoor comfort. As deeply described in Section 5.1, a variation of the set point temperature of 2 degrees allows storing 0.03-0.09 kWh for floor square meter.. As a conclusion, depending on the values of the heat capacity and thermal conductivity, buildings are more suitable for different type of DSM (long term, flexible, etc), as shown in Fig. 7. In particular, as shown in [88] the houses built after the 1980s had the highest potential for thermal mass utilization.

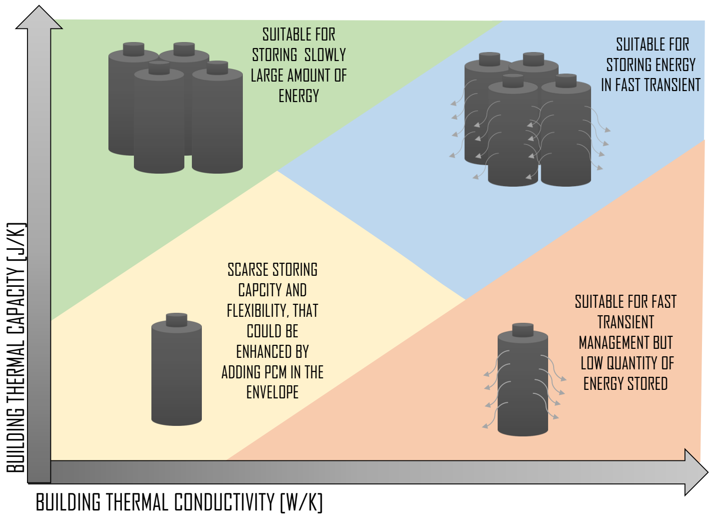

Figure 7. Equivalence building-thermal storage depending on envelope thermal capacity and thermal conductivity

The time constant allows performing experimental tests, or detailed simulations, on few buildings and then extend the results of the analysis to all the others. This approach has been used in [32] and [69]. In [82], because of lack of information, the buildings subjected to DSM are compared to others with known time constant.

Actually, in [89] the degree hours, is proposed as considered more effective than the time constant. A comparison between use of time constant and degree hours for DSM management revealed that degree hour can be a much complete quantity for taking into account indoor condition variation.

In other works, [75,78], DSM is implemented considering only small load shifting of the thermal demand (e.g. lower than 20 minutes) with the aim of not significantly affecting the indoor temperature. Actually in [75] it is shown that in case larger load shifting should be admitted, effectiveness of DSM significantly increases (going from 20 to 60 minutes, effectiveness of peak reduction increase up to 250%).

In [25] modifications of the indoor conditions are monitored by thermocouples installed in the rooms of the building. An average value is considered as the mean building condition. This can be used to properly select operations for demand side management. This is a good practice in case of pilot tests or applications to a small number of buildings, since building capacity of the envelope can be completely exploited. However in case of more extended applications, two main problems arise. The first is the cost of installing various thousands of thermocouples while the second concerns the fact that thermocouple installations can be not accepted by the end-users. In this framework, further legislative intervention and proper win/win campaign should lay the foundation for a profitable information exchange in a context of data protection.

The modeling analysis performed in [90] shows that the potential of DSM without downgreading the indoor temperature is larger in case of multi-family dwellings and non-residential buildings, since these have higher thermal capacities and, therefore, greater potentials for storing the energy. The single-family dwellings due to their lighter structures and higher surface area-to-volume ratios, are more subject to indoor air temperature reduction during DSM operations.

Inverse models are used in [44] to analyze potentials of the envelope as a storage, taking into account the building behaviour, based on measured data.The best strategy considered for summertime operations resulted in approximately a reduction of 40% in total cooling costs, compared with a traditional control. The work takes into account various analysis previously done with the aim of finding the best control strategy for a house to minimize the energy costs [91–94]. Various compact, or reduced order, models are proposed to analyze building response to DHSs. In [77] a compact physical model including building and substation set by using data collected in the building thermal substations (used for billing purposes) is proposed. This allows evaluating the evolution of the indoor temperature before and after DSM implementation. A clustering approach can also be used, as proposed in [69] for achieving DSM potentials for each building with similar characteristics. A similar model is proposed in [83], consisting in a mathematical link between the weather forecast (temperature and solar irradiation), the comfort level (deviation of the mean set-point temperature from the standard comfort temperature) and the supply water temperature. A detailed compact building model is shown in [95]; this is a Modelica-based building simulator that is able to efficiently support the development of DSM control strategies. Another interesting model built in Modelica is presented in [96], including in detail the heat transferred by ceiling, floor and walls; the model has been validated by comparing results to real-life data and literature. A similar thermal capacity-resistance model has been used in [60] to quantify the effects of DSM applications.

4.4. Accounting for network dynamics

DSM goal is usually adopted to achieve benefits on the production side. An estimation of the best thermal profile should be done at plant level and not at a building level. It is worth to remember that, because of the intrinsic dynamics of the network, the summation of the thermal requests of the buildings might be dramatically different from that at the power plant especially in the case of large networks [97]. The reasons are a) thermal losses (that can be large especially in distribution networks [98]) b) long thermal transients due to the water velocity in the pipelines c) continuous mixing of various streams at different temperature in various point of the networks. The large difference between demand at building level (i.e. sum of the building loads) and plant level (i.e. the overall demand cause by the building loads and the network thermo-fluidynamics) is deeply analyses in [68]. It is crucial taking into account the network dynamics. A simple example consists in considering the application of load shifting to users with equal schedule and located at the same distance of the thermal plant. It is clear that theoretically the shifting action would produce a simple shifting of the entire request; this is not true in case the thermo-fluidynamics is taken into account.

Modeling of thermal transients in DH network has been deeply analyzed in the literature [99–102]. This can be done by means of a thermal-fluidynamic model of the network. The main problem related with the use of such models in DSM decision intelligence concerns the dramatic increase of computational costs. Compact physical models can be alternatively used in large networks, as shown in [100].

4.5. Decision Intelligence

DSM is usually applied to an ensemble of buildings. The effect of an action performed on a building is directly related to the actions applied to the other buildings, therefore a combined approach is the best option in terms of results. For this reason, a decision intelligence, which applies an optimization algorithm, is preferred, as shown in Fig. 5.

Various types of decision intelligence are used in the literature. In [31, 32, 76, 103] agent based approaches are used. These allow simulating a system by means of multiple agents operating on a single building (or a limited set) and interacting with the others to converge to a global optimal solution. This approach is particularly useful in case various actors (agents) move towards their specific interests. On the other hand the selection of suitable number of parameters, features, and behaviors can be challenging, since to obtain meaningful results, the number of variables should be as low as possible while the number of agents and runs larger [104].

Heuristic optimization approaches are used in [78], [77], [75]] with the aim of finding the best set of schedule anticipation. Adoption of euristic methods (e.g. genetic algorithm) easily allow managing nonlinear objective functions and getting rid of possible local optima. The main drawback of euristic approach that the procedure becomes slower than with a gradient based method. For this reason it make sense to use them only in case of non-linearizable problems .

Another approach consists in using model predictive control [105]. This approach has the advantage that can be used to control nonlinear processes, optimizing the current conditions while taking into account the future. Respect to classic control methods it has the advantages of being more precise including the possibility of changing the setpoint. This option has been used in [83] to optimize management of DH including the application of DSM. In [82] a model predictive control is used along with a stable roommate algorithm as decision intelligence to modify the schedule of various buildings to achieve the best load fraction improvement. The idea behind this is to find a set of options (roommate selection) so that each roommate prefers more his roommates.

4.6. DSM implementation

Once the best DSM is selected for each building, the information must be properly sent to the control system in order to put it into practice. The control system should be able to read the information from the DSM decision intelligence and transform it into a signal for the control valve. The most used strategy in DH substations is based on a climatic curve, as shown in Fig. 8. The climatic curve relates the supply temperature at the secondary circuit (supply set point temperature, $T3_{sp}$), with the external temperature (T_{exp}). A valve installed in the primary circuit is opened or closed depending on the supply temperature $T3$. If $T3$ is lower than $T3_{sp}$ (that only depends on T_{exp} following the climatic curve), the valve opens, while the valve closes in the opposite case. The control logic is often proportional-integral [106]. During the night, two main approaches are used to reduce the heat supplied to the end-users. In some cases, especially in central areas of Europe, a setback strategy is used, by changing the $T3_{sp}$. In other areas, such as Mediterranean, the systems are often switched off during night. In both cases, $T3$ significantly differs from the set-point value $T3_{sp}$ in the morning therefore the valves open in order to increase the circulating mass flow rate as much as possible. For this reason high peaks are usually registered in the demandin both the cases; examples are Turin [78] (the largest DH in Italy, where night switch-off is adopted) and Aarhus [107] (the second largest DH in Denmark, where the set-back is adopted). In case proper measurement system is installed in the rooms of the buildings, the same kind of management can be performed by adopting the indoor temperature as the regulation variable (that should be larger than a set-point value) [108].

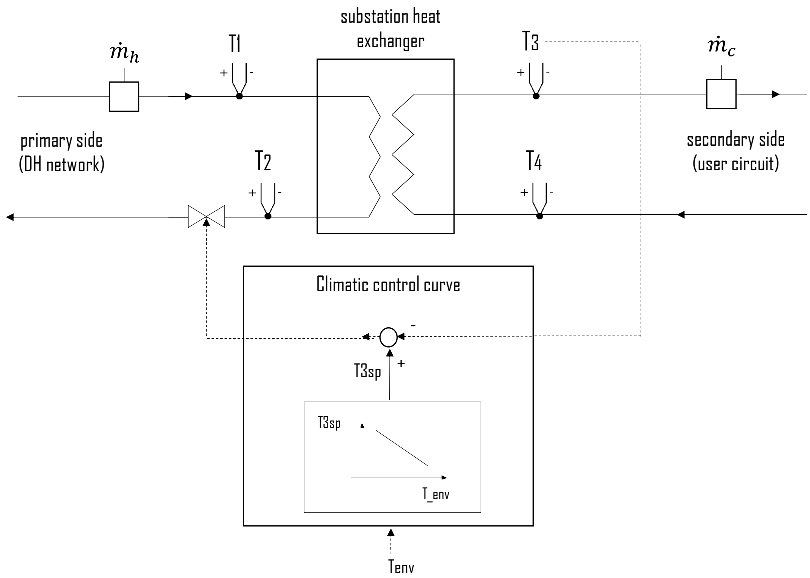

Figure 8. Schematic of a regulation system of a DH substation

DSM can be applied to a DH substation by acting on the control systems in different ways:

- The most diffuse is to force a change in the input of the climatic curve. The environmental temperature measured can be modified before entering the control system, as proposed in [89], such that the heat flux provided increases or decreases, depending on the type of DSM application.
- Another option consists in changing the climatic curve settings [25]. In this case the curve is directly modified. This is similar to the use of the night setback.
- In alternative, the supply set point temperature $T3_{sp}$ can be modified after being calculated by the climatic curve [31, 76].

- A different approach consists in shifting the time the heating system operates in normal conditions. This means modifying the time the heating systems are switched on or the end of the setback period [78, 83].
- A new option that can be adopted concern the change of the regulation technique. In [109] a specific innovative regulation approach called Differential of Return Temperatures (DRT) is applied and tested to shave thermal peaks. The test results show that the innovative regulation strategy allows peak reductions up to 25% in a DH distribution network.

These techniques can be used for peak shaving in both cases the peak is caused by complete switching off or setback.

5. DSM tests and applications

The most relevant and specific applications of DSM available in the literature are summarized in Table 1 and Table 2. Table 1 reports the experimental test, while Table 2 reports other kind of analysis and simulations. For each specific work, the goal, decision intelligence, way to taking into account of building indoor condition and network dynamic, implementation on the control side and results are reported. replaceThe table includes both simulation and real applications.

5.1. Building Analysis

Among the experimental tests on the use of buildings as thermal storage, in [25] a field-test is proposed to prove the effects of DSM in a university building connected to a DHS. DSM provides heat when the cost is lower and vice versa. 11 different DSM logic have been tested. The inlet water temperature, the indoor temperature and the level of occupant satisfaction are measured. Deviations in water temperature, between actual and expected values without DSM, have been set in the range +10/-20 °C. The test proved that DSM can be performed without significant impacts on occupant satisfaction.

Effects of DSM on indoor comfort conditions have been analyzed in [89], by experimental tests on 5 buildings in Goteborg (Sweden). Results show that storing $0.1kWh/m^2$ of floor area will very rarely cause variations in indoor temperature larger than 0.5 $\pm$°C in heavy buildings. DSM management effects are investigated for different types of building materials (wood, stone, tower-blocks, old brick) by experimental tests in [47]. The analysis proves that time constant may significantly change. In [**?**] is shown that increasing or decreasing the set point temperature of 2 degrees the energy flexibility that can be reached in Danish family houses is respectively 0.087 kWh/m3 and 0.036 kWh/m2 (values become 0.067 kWh/m2 and 0.025 kWh/m2 in case of apartment blocks).

5.2. DSM in DH analysis

DSM has been applied to an entire distribution network (about 100 buildings) in Turin (Italy) [75]. About one third of the buildings connected to the distribution network have a changeable schedule and are subjected to DSM. This is done to reduce maximum peak load to avoid bottlenecks. Indoor conditions are not considered since modifications in schedule are always lower than 20 minutes, but the effects of the network dynamics are taken into account by means of a thermal-fluidynamic model. Results show that peak reductions up to 10% can be achieved. In the same work, simulations have been used to estimate the effects of load shifting larger than 20 minutes. Results show that peak reduction can be of the order of 30%.

28 buildings in England have been subjected to DSM application, with the aim of increasing the load factor by means of a Stable roomate alghorithm [82]. Experimental results show that load factor may increase from 0.2 to 0.44 together with an increase of 3% in the energy demand.

An experimental analysis has been performed in Sweden on 14 buildings, forcing the total request evolution below a pre-selected threshold value that should not be exceeded [76]. The intelligence is based on the Agent based approach, while indoor conditions are estimated by mean of the time constant. The action is obtained by changing the supply temperature (T_{3SP}) with respect to that indicated by the climatic curve. The results from the field-tests show a significant profit for the end-users, and the district heating company. The amount of energy consumed can be reduced of 4%.

A field test was performed in Karlshamn (Sweden) on a distributed load control system to shave load to even out the daily fluctuations normally found in the energy demand in DH [31]. The DSM system is built with an on/off control scheme, which gains a proportional control property during dynamic use. Detailed measurements of indoor conditions proved that efficient DSM actions are possible without compromising the service quality delivered to the customer.

A specific field test was conducted in [27] on 27 buildings (student apartments) built between 1928 and 2009 in Finland (Tampere) and connected to a DH system. The demand response proposed consists in prioritizing domestic hot water demand at the expense of the heating. This causes an indoor temperature decrease when demand for domestic hot water is high. The peak load decrease was 14%–15% (during the coldest days) and a 9% reduction in energy, costs and greenhouse gas emissions.

Various simulation tests can be also found in the literature. Interesting tests have been performed on three buildings (two in Finland, Jyvaskyle, and one in German, Mannheim) as shown in [60]. Tests on real buildings are performed in [110] to analyze optimal demand response control algorithms from a building owner's point of view. In both cases, results show reductions of the peak of about 20-30%. An interesting simulation was done in [111] on actual domestic hot water consumption data measured in a 12-storey dormitory with 159 apartments in Aarhus (Denmark). The network is supposed to be supplied at low temperature with heat pumps. A price based demand response for peak reductions and energy cost savings is proposed through a model predictive control approach. With this approach effects are achieved in terms of both electricity and thermal peak reduction. A simulation of a building connected to a DH is shown in [112] to evaluate potentials of DSM when applied to ventilation systems; results show that the maximum savings achievable are: 3% for heat consumption, 6% for the heating cost and, considering a variable air volume system, 8% for the heating consumption 11% for the heating cost, 9% for the electricity consumption and 2% for the electricity cost.

An occupant behavioural model is built in [113] to study the behavior Demand Response (i.e. a demand side driven by occupants that are asked to participate and temporarily alter their demand profiles). The behavioral occupant model takes into account the motivational factors and the financial incentives. This is shows that can be integrated with district heating model and tested on 12 rooms of an Irish campus. Results show that an energy savings of up to 4.5% was achieved.

Table 1. DSM experimental analyses in DHSs

Ref	Goal	Intelligence	Account for effects on buildings	Account for network effects	Regulation	Exper. tests	Results
[75]	avoid bottlenecks	genetic algorithm	none since load shifting are limited to 20 min	yes, the return pipeline dynamic is considered	change of the schedule (anticipation of the switching on time)	about 35 buildings in Turin (Italy)	peak shaving between 5% and 35% can be achieved
[82]	improvement of the load factor	ttable roommate algorithm	estimation of time constant by comparison with buildings of other analysis	no	the demand coordination software changes schedule of half of buildings	28 buildings (England)	from 0.2 to 0.44 of load factor but increasing of 3% of the energy demand
[76]	load of the system kept below a threshold value	multi-agent intelligence	time constant	no	change in the supply temperature, respect to that indicated by the temperature control curve	14 buildings (Sweden)	energy reduction 4%
[89]	find how thermal inertial can be used as storage for DSM	-	degree hour has been found more effective than time constant	no	signal to the regulation system in increased or decreased in order	5 buildings in Goteborg (Sweden)	a storage of 0.1 kW h/m2 of floor usually causes variations in indoor temperature lower than 0.5
[31]	load of the system kept below a threshold value	multi-agent intelligence	indoor temperature measurements	no	change in the supply temperature, respect to that indicated by the temperature control curve	SWEDEN (Karlshamn)	significant difference in the average deviation of the demand from its mean value

Table 1. DSM experimental analyses in DHSs

Ref	Goal	Intelligence	Account for effects on buildings	Account for network effects	Regulation	Exper. tests	Results
[47]	mass of buildings is investigated to eliminate daily load variations	no (load shifting are performed to quantify effects of load modification)	measurements	no	shifting radiator supply temperature, manually	test with different types of buildings (wood, stone, towerblocks, old brick) in Goteborg (Sweden)	Time constant dramatically change depending on the building material. Variation of the outdoor temperature can reach 10-20°C to smooth daily peaks in Sweven
[60]	reduce peak demand	do not propose a particular intelligence but tariff changes	no	no	shifting heat demand to night or early morning	3 buildings in Finland and Germany	Peak cut of 25-30% can be achieved
[27]	reduce peak demand	the algorithm reduces the heating power when domestic hot water peaks occur	the system requires indoor temperature sensors	no	prioritizing domestic hot water demand (at the expense of space heating)	27 buildings of student apartment (1928-2009) in Finland (Tampere)	peak reduced up to 15% and energy/cost/emissions reduced up to 9%
[114]	prevent the draught risk of cold window	model predictive control	measurements using a thermal manikin	no	an optimization algorithm to evaluate the optimal temperature setpoint curves and a two capacity RC-model (for load forecast)	the 4th floor of an office building of Aalto University	energy cost reduced by 3% to 5% with different windows
[108]	investigate potentials of the built environment for DSM	-	temperature sensors in various rooms	no	regulation is done by keeping the measured indoor temperature larger than a set point value	Field tests in 13 homes equipped with ICT technologies performed in Copenhagen	the peak-hour energy consumption reduced by 85% with little impact on energy consumption and indoor temperature

Table 2. DSM studies in DHSs

Ref	Goal	Intelligence	Account for effects on buildings	Account for network effects	Regulation	Experimental tests	Results
[25]	test effects of DSM on comfort of end-users when a cost reduction is the goal	Dreau and Heiselberg algorithm	thermocouples distributed indoor are used (by averaging them) to measure the effects of DSM	no	change of temperature set value	no	DSM can be performed without significantly impacting occupant satisfaction
[32]	level out total thermal power	agent based intelligence	simplified bulding model to achieve the time constant	no	-	no	it is possible level out the thermal load under prescribed values
[78]	minimization of peaks and minimization of energy produced by Heat-only-boilers	genetic algorithm	none since load shifting are limited to 20 min	yes the return pipeline dynamic is considered	change of the schedule (anticipation of the switching on time)	no	peak reduction up to 6%, primary energy consumption reduction up to 1%
[115]	minimization of thermal peak	euristic optimization approach	none since load shifting are limited	yes, both supply and return pipeline dynamics are considered	change of the schedule (anticipation of the switching on time)	no	peak reduction up to 30%
[77]	minimization of thermal peak	genetic algorithm	a building compact model is used to achieve the effects of DSM in term of temperature variations	yes, the return pipeline dynamic is considered	change of the schedule (anticipation of the switching on time	no	yearly primary energy consumption -5%
[83]	minimization of the combination of power price and comfort violation over a future horizon of 24- hours	Model Predictive Control	Semi-physical building compact model	no	load shifting	no	the control proposed adapts with energy prices predictions and shifts the load accordingly

Table 2. DSM studies in DHSs

Ref	Goal	Intelligence	Account for effects on buildings	Account for network effects	Regulation	Experimental tests	Results
[110]	simulation on real building to analyze optimal demand response control algorithms from a building owner's point of view	rule-based algorithms based on a dynamic heat price	dynamic simulation using the tool IDA-ICE	no	-	no	peak shaving of 35% can be achieved without significantly affecting indoor conditions
[50]	improve penetration of wind considering thermal and electrical DSM	mixed integer nonlinear programming optimization by outer approximation with equality relaxation	indoor temperature evaluated considering the building as a storage with an equivalent capacity	no	-	no	the negative impact in actual operations due to the unpredictability of wind power can be reduced
[79]	maximizing the profit of integrated energy service agency	interior point method	model based on the energy balance of the building considered a single air volume	no	-	no	the energy expenditure of the multi energy system can be reduced by 19% .
[111]	price minimization in a ultra-low temperature DH supplied by heat pumps	model predictive control	no (the work is applied on domestic hot water)	-	heat pumps are operated depending on the outcome of the model predictive control	no	the yearly cost saving that can be achieve is about 5% .
[116]	minimize the overall thermal discomfort and maximize the thermal fairness	optimization for multiple time frames (no algorithm specified)	indoor temperature evaluated using a resistance-capacitance model	thermal losses considered	optimization of the mass flow	no	reduction of supply temperature can be obtained by use of DSM (depending on the objective function adopted) .

Table 2. DSM studies in DHSs

Ref	Goal	Intelligence	Account for effects on buildings	Account for network effects	Regulation	Experimental tests	Results
[112]	price minimization (considering a dynamic district heating cost)	rule-based demand response strategies	indoor temperature evaluated using a validated dynamic building simulation tool	no	regulate room air setpoint temperature	no	Maximum yearly savings by DSM of space heating and ventilation: 3% for the consumption and 6% for the cost.
[26], [117]	minimization of energy consumption	agent based approach	indoor temperature evaluated through a compact model	fluid-dynamic (no thermal)	-	no	11% reduction of the energy cost.
[90]	investigate demand and indoor temperature variations in different kind of buildings with and without presence of thermal storage	mixed-integer optimization	physical space heating model	no (but heating losses considered)	load shifting	no (but case study: 134 representative buildings in Gotheborg)	indoor temperature variation strongly depends on the type of building and presence of thermal storage
[51]	optimal integration of limited temperature sources	building model based on energy conservation equation	no (but heating losses considered)	best estimation of the demand evolution	no	peak reduction up to 55%]	

5.3. Discussion

It is not easy to put together the information gathered during the review work to perfectly give an idea of the benefits that can be obtained by DSM application to DHS.

Concerning analysis of building envelope, the works reported show that it is always possible storing a certain quantity of energy without compromising indoor condition [89], [25]. Clearly the amount of energy strongly depends on the type of building envelope, occupancy schedule and climate conditions [47, 118].

In several works [60, 69, 78, 119], both experiments and simulations, it has been shown that DSM allows achieving significant peak reduction (usually between 10 and 30%), possibility of keeping demand below a certain value [76] and increasing the load factor [82]. Therefore, the effects of DSM in peak reduction are proved, although the specific amount of the effects depends on the dimension of the peak, kind of building and action that is applied.

Regarding the effects on energy saving and cost the point it is more difficult. Various works prove reduction of energy consumption [77], [76] and costs [25, 88, 90]. Actually also non completely positive results have been achieved. DSM is shown to produce only slightly positive effects on costs [120]. In the same work it has been stated that the profitability varies with the thermal plant types and network characteristics [120]. However the savings that can be obtained in a building is sensitive to such many factors, including heating system schedule, characteristics of the buildings in the same area (envelope, volume and use), network dimension and topology, climate conditions and control strategy. An option to increase potential of DSM consists in combination of water tank storage and DSM; this as been shown in [90, 120] is very promising in terms of cost and emission reduction. In [121] impact of DSM on costs are analyzed from end-user and company perspective. Results show that the benefits that can be achieved significantly depend on how the DH system is originally planned. Furthermore the cost saving depend on the indoor modifications allowed; in [90] is shown that the total cost decreases by 9% when only upward temperature deviations are allowed and by 11% with both upward and downward temperature deviations allowed. In [88], economic savings in operational costs of DH have been accounted for the city of Sønderborg for 0.7%–4.6%, not taking into account the cost of smart controls. Combined application of storage and demand side is deeply discussed for island application in [122]. In [90] integration of DSM and thermal energy storage are analyzed. The DSM applied in the presence of a thermal energy storage decreases while by applying both DSM and centralized thermal energy storage allows achieving the lowest operation cost for the DH system.

Another important point concerns the greenhouse gas emissions. Supply the peak demand means in operating the peak units which are usually fed by fossil fuel, producing the highest rate between the emission and the produced thermal power. The peak shaving and valley filling allows reducing the adoption of such kind of devices, increasing the utilization rate of the most advanced plants. In [120] is shown that DSM only produces a slight positive effect on emissions; on the other hand in [27] is estimated that significant emission reductions can be achieved by DSM (up to 9%). The differences in the results achieved mainly depends on the differences of the technologies used to cover peaks and base loads (from an emission perspective), and also by the thermal load profiles without DSM. A flatter thermal demand also enhance potentials for the exploitation of renewable energy (thermal or electrical converted in thermal by means of heat pumps), waste-heat and low-grade heat available from industrial plants. In case of strong availability of these kind of sources, proper control can strongly improve the effects achievable by DSM.

DSM application involves among the stakeholders, the building/flat owners, which are the costumers of the service. They play a significant role since the modification in the thermal demand can be performed only if this is accepted or required by the costumers. Monetary incentives and personal motivation play both a crucial role. Several studies on the effects of incentives have been performed in the electric demand response [123–125]. Concerning district heating few studies can be found specifically on the DSM incentives. In an interesting work [59], was found that proper incentives should be adopted when the aim is the thermal peak reduction, otherwise peak shifting is achieved instead of peak shaving. In [126] the potential tensions created by the adoption of various kind of DSM and demand response actions are discussed. From the costumer perspective, a reduction of the fix cost, if provided for, is an interesting benefit to agree to the modification of its own demand. Indoor comfort and domestic hot water availability are usually commodities of prior importance for the users, therefore specific agreements should be set to define effective pathways. On the other hand the cooperation between the energy provider and the users has significant potentials in increasing the benefits of DSM [120]. A well-structured design of the DSM organizational system, including the various stakeholders (component supplier, energy company, housing company, maintenance company) is important to maximize the benefits achieved. A conceptual process, based on interview, analyses and participants observations during a DSM real application, is proposed in [127]. The work demonstrate that: a) the perception of the utility of DSM enhance the propensity of the stakeholders to invest and their interaction b) providing a combination of services including DSM, improve the diffusion of DSM c) independent core technologies and clear rules help overcoming the barriers due to the technology novelty d) define collaborative governance of the provider for DSM devices/services improve the obtainment of technological solutions.

6. Conclusions and future perspective

This paper provides a survey on the use of DSM district heating networks. This is done by discussing one by one the stages for its implementation in district heating systems taking into account how they have been tackled in the various works available in the literature. Stages for DSM implementation can be summarized as: a) selection of the quantities affecting DSM and goals to be achieved b) creation of an adequate decision intelligence to combine properly DSM actions for all the involved buildings c) inclusion of indoor conditions control and network dynamic impact d) application of DSM actions to the control system. Different kind of DSM actions are discussed, along with the advantages that can be achieved. Both simulation and real application are considered in the review. Various experimental tests have been performed on district heating. Some analysis are done to study potential of buildings as thermal storage for DSM, in others DSM decision intelligent are tested. Demand side management in district heating systems is shown in the various works available in the literature that allows achieving:

- Peak shaving up to 30%.
- Reduction of primary energy needs up to 5%.
- Load factor doubling.

- Emission and cost reduction strongly dependent on the system characteristics (up to 10%).

It is not possible to identify a unique best solution for DSM implementation because DH systems can be very different in terms of a) DH operating conditions b) thermal plants c) goal to be achieved d) end-user habits and behavior e) network topology and dimension. However, the analysis performed revealed various research path that should be more investigated in future:

1. Application of new control strategies to achieve lower thermal peaks when night setback ends.
2. More complex reshaping of thermal load, not only by shifting.
3. Deeper analysis on use of retrofitting activities for enhancing effects of DSM actions
4. Application of DSM to district cooling systems.
5. Definition of procedure for the selection of DSM applications depending on DH plants and substation operations and system size for reducing primary energy consumption and costs. This could enhance the diffusion of DSM to DH systems that is now at a starting stage.
6. Further studies on the combination of thermal inertia of network pipelines and building mass to increase DSM potential.
7. Stochastic analysis for taking into account effects of uncertainties (weather, consumption and cost unpredictability) on the benefits obtained by mean of DSM. This allows quantifying the robustness of the action proposed.

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