Evaluation of Energy Flexibility From Residential District Cooling

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Abstract

Space cooling represents one of the fastest growing energy demands in buildings. Without any action to increase energy efficiency, this trend will be confirmed in the next decades, contributing significantly to the peak electricity demand growth. The need to increase both the energy efficiency and flexibility of the air conditioning (AC) sector is so urgent because of the strong penetration of renewable energy sources (RES) in the electricity generation mix.
District cooling (DC) systems are recognised as one of the best solutions to reach this goal. As the DC energy efficiency benefits are not questioned, the objective of this paper is to provide a qualitative evaluation of the potential of DC networks in terms of energy flexibility. By modelling a small residential neighbourhood to be satisfied with a given cooling power availability, the effect of the different DC thermal inertia levels (e.g. the pipelines network, the buildings envelope and a dedicated thermal energy storage device) is investigated by means of two qualitative flexibility indicators (the wasted cold energy and the overheating time). The analysis shows that a great potential of energy flexibility is contained in DC systems. In particular, a great thermal demand management potential can be obtained when the buildings envelope thermal inertia is activated properly.

1. Introduction

The United Nations Environment Programme (UN Environment, 2018) estimates that the energy consumption in the refrigeration, air conditioning (AC) and heat pump (HP) sectors is expected to surge by a factor of 33 by 2100. In particular, space cooling seems to be the fastest growing sector, having more than tripled, between 1990 and 2018, its energy demand (IEA, 2019). More than 1.6 billion air conditioning units are now in operation around the world, making it the leading driver of new electricity demand in buildings (IEA, 2019).
Although the AC sector has in recent years reached high-performance levels (Carrier launched a new AC unit in early 2018 with a SEER of 12.3), the most widespread technologies among users are far from reaching such levels of performance. Moreover, a growing spread of localized AC technologies tends to increase the peak energy demand. Thus, the great impact of such energy demand on the overall electricity consumptions, combined with the increasing penetration of renewable energy sources (RES), whose generation is discontinuous and uncertain, make it necessary to plan strategies to improve the energy efficiency and flexibility of the AC sector, i.e. Demand Side Management (DSM) strategies.
District cooling (DC) is identified as a possible solution to fulfil this demand in a more efficient and flexible way (Connolly et al., 2012). The EU Energy Efficiency Directive (EED) has recognised DC systems as one of the important pillars for achieving the energy efficiency target (European Parliament, 2012), and the SETIS report identifies the DC technology as the best available technology (BAT) for the Cooling market in the EU (Garcia et al., 2012).
Many are the strengths of DC: (i) different cooling production systems can be combined (e.g. vapour compression chillers, absorption chillers, free cooling, …) (Passerini et a., 2017), (ii) containing different levels of thermal inertia, it can make the AC sector, whose energy flexibility is low (Arteconi et al., 2019), more suitable for load management and (iii) it allows the implementation of thermal energy management strategies at district level.
There are many studies in the literature that prove the energy benefits of district heating networks, but not much can be found on DC. With this paper we

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will provide a preliminary qualitative analysis of the energy flexibility that can be obtained from a small residential district cooling network. By means of a dynamic simulation model of a residential neighbourhood, the effect of the different thermal inertia levels available in the DC plant is investigated, in an attempt to maximize the use of available cooling energy while maintaining indoor thermal conditions of the users.

2. Methods

In DC systems the achievement of good environmental sustainability levels is closely linked to the flexibility of the network. The management of non-simultaneous energy demand with supply would be very difficult with low flexible systems. In this work the energy flexibility of cooling networks is defined as the ability of the overall DC to manage and uncouple its energy demand and supply.

In a DC system three levels of thermal inertia can be exploited (Vandermeulen et al., 2018): (i) the network, (ii) the buildings envelope thermal mass and (iii) the contribution of a dedicated device added to the DC plant, as a thermal energy storage (TES) system.

In this paper each of these contributions is evaluated by means of daily energy simulations (with a timestep of 10 minutes) of a hypothetical residential district realized in TRNSYS (Solar Energy Laboratory, 2012). The thermal inertia contributions are activated when there is a cooling demand but there is no more cooling availability on the supply side. Each thermal inertia contribution is activated as explained in the following.

The network contribution (i) is represented by the thermal energy carried by the fluid in the pipes. The fluid can satisfy the users requirements and warm up until a limit condition occurs (i.e. thermal balance with the ground temperature). The second thermal inertia contribution, the building inertia (ii), is activated with a control strategy on the users' temperature set-points. The building thermal mass is used as passive thermal storage with a pre-cooling of the living areas with programmed lowering of the users' indoor temperature. The last thermal inertia contribution (iii) is represented by a sensible TES of different sizes.

In the analysis, a hypothetical daily profile of available cooling thermal power, which is assumed to be recovered from a technological process (e.g. natural gas regassification plants), is provided to the district as a cold flow rate available at a given supply temperature (further details are reported in Section 3). It is assumed that the cooling power profile is able to satisfy the average daily cold energy demand and the peak cooling power demand of the district (derived by the sizing procedure exposed in Section 3) but with a random time displacement between demand and supply curves (Fig. 1).

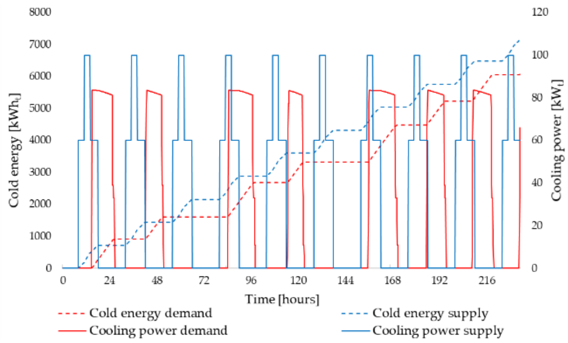

Fig. 1 – Daily cooling power and cumulative cold energy demand and supply for the residential district

Since the purpose of an optimal network management is the minimization of the wasted available cooling load, two qualitative indicators are calculated to assess the DC network flexibility potential.

1. The wasted cold energy, defined as the percentage of daily energy actually used compared to the given supply cooling energy availability.
2. The overheating time, defined as the hours per day in which the user comfort (comfort condition set at 26 °C) cannot be maintained.

These two indicators are obtained from the energy simulation results of the district described in the following section and they are calculated for the day in which the daily users cold demand is closer to the average cooling supply. In this way, the wasted cold energy is mainly due to a not effective use of the energy flexibility rather than to a difference between energy demand and supply. The results of the evaluation are shown and discussed in Section 5.

3. Case Study

In this work the DC flexibility potential of a small residential cooling network (14 users) is investigated. Users are located in Rome (41° 55' N, 12° 31' E) and modelled as modern single-family houses (SFH) (data for SFH built after 2006 derived from Tabula project (Corrado et al., 2014)). In Table 1, 2 and 3 the structure composition and the thermal properties of the materials (UNI, 2014a) of the external walls, roof and floor are reported.

Type 88 of TRNSYS is used to model each building which is composed of a single thermal zone with a simple lumped capacitance structure. Two parameters are required by Type 88 to define the building thermal inertia: the overall building loss coefficient and the building thermal capacitance.

As average value of the thermal transmittances of the different parts of the building envelope (calculated with values reported in Table 1,2 and 3 (UNI, 2008)), the first parameter is equal to 0.38 W m^{-2} K^{-1}. The second one is assumed to be 68.66 MJ/K. It is calculated according to the UNI EN ISO 13790 (UNI, 2008) considering the building structures described in Table 1, 2 and 3.

The single building is composed of two floors and has a living area of 160 m^2 (80 m^2 per floor). For each external wall, 8 % of window surface area rate is considered. Solar radiation is provided as internal gain to Type 88 according to the procedure reported in the Italian standard UNI TS 11300:1 (UNI, 2014b) with irradiation data contained in the weather file, obtained with Meteonorm V 5.0.13 (TESS, 2013). As far as the occupants' gains are concerned, 4 occupants are considered for each building and a corresponding internal gain of 110 W/person is introduced. Artificial lighting accounts for a power density of 5 W m^{-2} and it turns on if the total horizontal radiation is less than 120 W m^{-2}, while it turns off if radiation is greater than 200 W m^{-2}. The contribution of natural ventilation is introduced too, assuming air changes per hour equal to 0.5 h^{-1}.

The building cooling distribution system comprises fan coil units (FCU) modelled with Type 996. Cold water is supplied at a design temperature of 7 °C, with a temperature difference between delivery and return of 5 °C (Fig. 2 reports the TRNSYS model of the single user connected to the DC).

Table 1 – External Wall structure: materials listed from inside to outside with their thermal properties (density, thermal conductivity and heat capacity)

Material	s [m]	ϱ [kg/m³]	λ [W/(mK)]	c [J/(kgK)]
Internal plaster	0.02	1400	0.70	1000
Hollow bricks	0.08	800	0.40	1000
Thermal insulator	0.08	30	0.04	1250
Bricks	0.25	1800	0.72	1000
External Plaster	0.02	1800	0.90	1000

Table 2 – Roof structure: materials listed from inside to outside with their thermal properties (density, thermal conductivity and heat capacity)

Material	s [m]	ϱ [kg/m³]	λ [W/(mK)]	c [J/(kgK)]
Internal plaster	0.02	1400	0.70	1000
Bricks	0.20	1800	0.72	1000
Concrete	0.05	2400	1.91	1000
Thermal insulator	0.12	30	0.04	1250
Roof tiles	0.03	2000	1.00	800

Table 3 – Floor structure: materials listed from inside to outside with their thermal properties (density, thermal conductivity and heat capacity)

Material	s [m]	ϱ [kg/m3]	λ [W/(mK)]	c [J/(kgK)]
Floor	0.02	1700	1.47	1000
Concrete	0.05	2400	1.91	1000
Thermal insulator	0.10	30	0.04	1250
Concrete	0.10	2400	1.91	1000

For the plant sizing, the design peak cooling demand is evaluated by means of the Carrier-Pizzetti (Pizzetti, 2012) technical dynamic method. For Rome, with the outside design conditions suggested by the standard UNI/TR 10349-2 (UNI, 2016), a daily sensible thermal load of 6.3 kWt is calculated (comfort conditions are set to 26 °C and 50% of relative humidity) with a latent contribution of about 2 kWt.

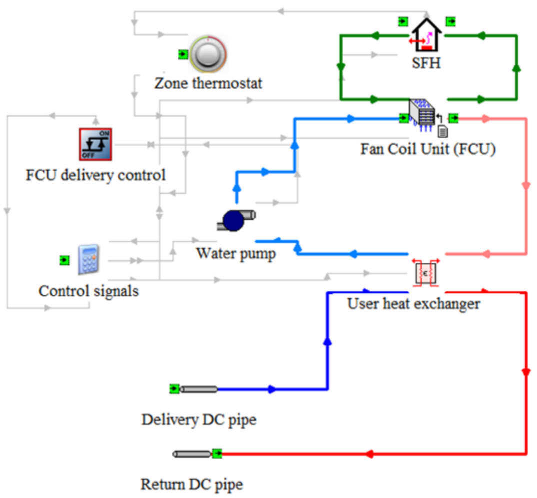

Fig. 2 – Single user model. Screen of TRNSYS Simulation Studio

The heat exchange between the FCU water circuit and the DC network is realized by means of a simple constant effectiveness heat exchanger (Type 91 in TRNSYS). It is a zero-capacitance sensible heat exchanger that requires the value of the effectiveness to calculate the actual heat exchanged compared to the maximum possible heat transfer (based on ε-NTU method). In our case a constant value of 30% is used for the heat exchanger effectiveness. This value is assessed so that the peak cooling power transfer among the water in the FCU circuit and the cold fluid in the DC pipes occurs at the design temperatures.

In Fig. 3 a scheme of the DC network is reported. A mixture of water and glycol is used as heat transfer fluid (Celsius SAS, 2019). In design conditions it is delivered at a temperature of -10 °C, with a design temperature difference between supply and return of 5 °C. The pipes are modelled as underground pipes (ground temperature of 14 °C) with Type 31. Type 31 models the thermal behaviour of a fluid flow in a pipe using variable size segments of fluid. Thus, it is possible to take into consideration the effects of heat diffusion delay along pipes.

Referring to real pipes used for district heating and cooling systems (Aquatechnik Group, 2013), large thicknesses (26-28 cm) of thermal insulation based on polyurethane rigid foam (thermal conductivity of 0.027 W m^{-1} K^{-1}) are considered to minimize the ground cooling energy losses. As far as the pipes' length is concerned, a distance between two close nodes (users) of 10 m is assumed for a total piping length of the district cooling of 200 m.

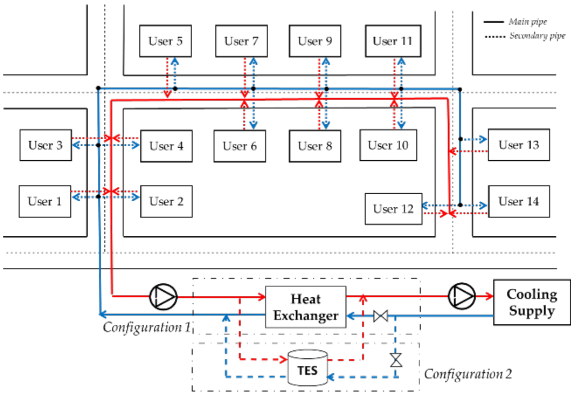

Fig. 3 – DC network plant scheme. Configuration 1: heat exchange between demand and supply realized with a heat exchanger. Configuration 2: heat exchange between cooling demand and supply realized with a TES

Two DC plant configurations, which differ on the interaction between the supply side and the demand side, are modelled (Fig. 3). In the first one (configuration 1) the heat exchange between the cooling demand and the supply is realized with a simple heat exchanger (Type 91). It is used to investigate the flexibility potential of the network and of the building envelope. The second configuration (configuration 2), by comparison, includes a TES on the demand side. It is a stratified cold-water tank, modelled through Type 4. In this case, the heat exchanger is not included and when there is cooling power availability, the heat transfer fluid enters directly into the cold side of the tank.

Different sizes of the tank are tested. The sizes are varied in order to guarantee the users' design cooling load for variable periods of time. When the temperature difference between the inlet and outlet tank flow rates is below 2 °C, the TES is considered discharged.

4. Results and Discussion

In order to evaluate the energy flexibility potential of the residential DC system described in the previous section, the results of the DC daily energy simulations are analysed. The discussion focuses on a single representative summer day. It is chosen as the day in which the DC available cold energy is closer to the DC average daily cold energy demand (820 kWht). In this way the evaluation of the wasted cold energy is significative, since it represents the amount of cooling demand that cannot be satisfied for the lack of flexibility of the system.

The first flexibility contribution that is investigated is that from the network. Fig. 4 reports the daily energy demand, supply and total heat exchanged by the heat exchanger on the supply side when the cooling power availability is directly combined with the cooling demand of the users (configuration 1).

As can be noticed in Fig. 4, the network flexibility contribution is low. At 7.00 pm, when there is no more cooling power availability, but users continue to ask for cooling, the network thermal inertia allows the demand to be satisfied for a very short time (about 25 minutes). The wasted cold energy is about 468 kWht (57 % of the total) with more than 4 hours of overheating (Table 4).

As far as the inertia of the buildings' envelope is concerned, a good flexibility performance can be observed. Fig. 5 shows the case in which the buildings envelope thermal inertia is activated for 1 hour (pre-cooling the buildings by lowering the internal temperature set-points by 1 °C) before the daily cooling demand occurs. In this case no overheating is measured and the wasted cold energy decreases to 337 kWht (41 %). Furthermore, different pre-cooling strategies to activate the buildings thermal mass are tested. The most interesting case can be noticed when the internal temperature set point is lowasd during the early hours of the day (for 3 hours, from 8.00 am to 11.00 am) by all the users simultaneously. Indeed, during this period, there is no cooling demand, but cold supply energy is available. The wasted cold energy becomes 13 % without overheating. However, it is important to underline that this solution needs predictive control and more sophisticated management systems to be implemented.

Turning to the TES flexibility contribution evaluation, it is clear from the results that it is the means that allows a simpler and better decoupling in real-time of demand and supply. In Fig. 6, the cooling energy demand and the supply availability, when a 4500 litres cold water tank (1 hour of autonomy) is added to the demand side, is shown.

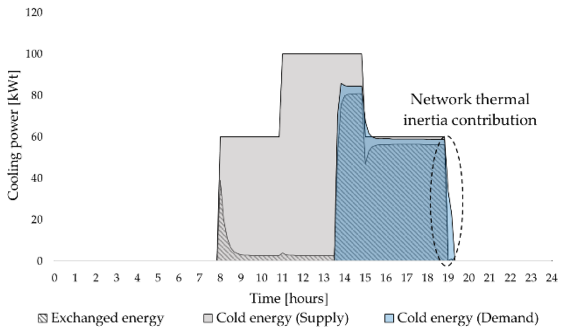

Fig. 4 – Daily cooling power demand, supply and heat exchanged in the case of DC system configuration 1. The dotted area represents the cold energy exchanged in the Heat Exchanger. The grey area is the free cooling daily availability. The blue area is the cooling energy demand of the district (all users)

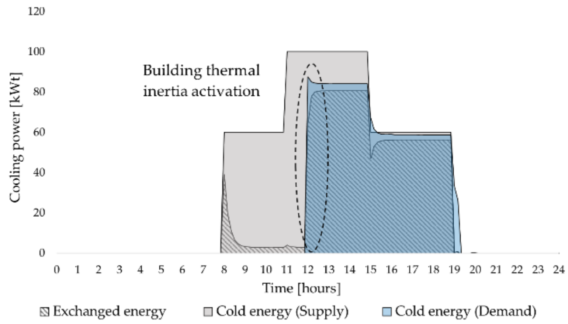

Fig. 5 – Daily cooling power demand, supply and heat exchanged in case of DC system configuration 1. Building envelope thermal inertia activation for 1 hour. The dotted area represents the cold energy exchanged in the Heat Exchanger. The grey area is the free cooling daily availability. The blue area is the cooling energy demand of the district (all users)

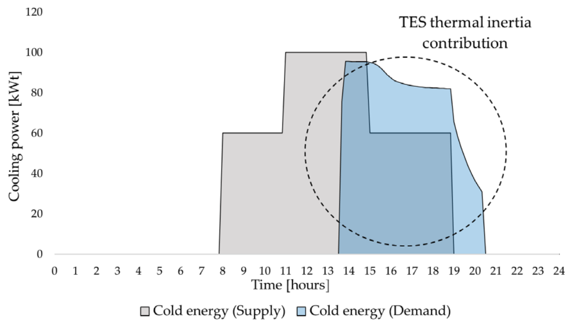

Fig. 6 – Daily cooling power demand and supply in the case of DC system configuration 2 with a 4500 litres TES (1 hour of autonomy). The grey area is the free cooling daily availability. The blue area is the cooling energy demand of the district (all users)

The thermal comfort can be maintained (overheating < 1%, Table 4) with 36% of wasted cooling energy (Table 4). Increasing the TES size, the energy flexibility performance increases as shown in Table 4. Practically without overheating (consistently less than 20 minutes), the wasted cold energy decreases, arriving at the minimum value when a

26000 litres TES (6 hours of autonomy) is used. However, comparing the TES flexibility with the building thermal mass flexibility (Table 4), it is interesting to notice that, assuming it is possible to control the inside temperature set-points with appropriate predictive control strategies, the activation of the thermal inertia of the buildings can also guarantee good results Indeed the building pre-cooling for 1 hour allows a similar flexibility as a 4500 litres TES, while a building pre-cooling for 3 hour offers the same flexibility as a 26000 litres TES (6 hours). It can therefore be concluded, even if a higher management complexity is required, a great flexibility potential is contained in the building envelope thermal mass. This result highlights how promoting the diffusion of smart buildings, whose energy demand could be managed by a district energy manager, can be a useful solution to optimize the energy sustainability and flexibility of the AC sector.

Table 4 – Qualitative indicators for the flexibility contributions analyzed. Wasted cold energy assessed as percentage of the average daily cold energy supply (820 kWht). Overheating hours as percentage of 24 hours

Flexibility contribution	**Wasted cold energy [%]**	**Overheating time [%]**
Network	57 %	18 %
Buildings (activation 1 hour)	41 %	0 %
Buildings (activation 3 hour)	13 %	0 %
TES 4500 litres (autonomy 1 hour)	36 %	<1 %
TES 9000 litres (autonomy 2 hours)	17 %	<1 %
TES 13000 litres (autonomy 3 hours)	19 %	<1 %
TES 26000 litres (autonomy 6 hours)	7 %	<1 %

5. Conclusion

The objective of this work is to provide a qualitative evaluation of the energy flexibility reserves that can be used in a residential district cooling system. The different thermal inertia assets of the network are investigated as flexibility providers and the main conclusions can be summarized in the following points: (i) as far as the network thermal inertia contribution is concerned, the pipelines provide a very small contribution: the cooling demand can be satisfied for less than 1 hour, when there is no cooling power availability. (ii) Assuming it is possible to control the inside temperature set-points of the users with appropriate predictive control strategies, the activation of the thermal inertia of the buildings, pre-cooling the buildings' thermal mass when the cooling supply is expected to be wasted, seems to have a great flexibility potential, comparable to the installation of a TES. (iii) A dedicated thermal inertia device is confirmed as the best means to decouple and manage in real-time energy supply and demand in the simplest way. In particular, the addition of a 26000 litres tank to the DC plant allows the best demand/supply balance with low discomfort levels.

Concluding, DC systems show benefits in terms of energy flexibility and environmental sustainability, since a good level of thermal inertia is present in the system. In this way it is possible to maintain the comfort of the users while maximizing the energy efficiency of the overall system.

In particular, the analysis highlights that investing in smart residential districts, managed by a district energy manager, could greatly increase both efficiency and flexibility of the AC sector.

Acknowledgement

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Nomenclature

AC	Air Conditioning
BAT	Best Available Technology
DC	District Cooling
DSM	Demand Side Management
EED	Energy Efficiency Directive
EU	European Union
FCU	Fan Coil Unit
HP	Heat Pump
RES	Renewable Energy Source
TES	Thermal Energy Storage

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