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Potential of District Cooling Systems: A Case Study on Recovering Cold Energy from Liquefied Natural Gas Vaporization

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Received: 30 June 2019; Accepted: 3 August 2019; Published: 6 August 2019

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Abstract: District cooling systems (DCSs) are networks able to distribute thermal energy, usually as chilled water, from a central source to industrial, commercial, and residential consumers, to be used for space cooling/dehumidification. As cooling demand will increase significantly in the next decades, DCSs can be seen as efficient solutions to improve sustainability. Although DCSs are considered so relevant for new city developments, there are still many technical, economic, and social issues to be overcome to let such systems to spread out. Thus, this paper aims to highlight the advantages and issues linked to the adoption of DCSs for building cooling when cold is recovered from a specific application. A case study based on liquified natural gas (LNG) cold energy recovery from the transport sector is presented. Starting from the estimation of the free cooling availability, a DCS design method is proposed and the potential energy saving is investigated. Results show that a DCS using the cold waste derived from LNG can provide a relevant amount of electricity saving (about 60%) for space cooling compared to traditional solutions, in which standard air conditioning systems are installed in every building.

Keywords: district cooling; liquid to compressed natural gas; thermal energy storage; energy efficiency; LNG

1. Introduction

Buildings are responsible for about 40% of worldwide energy use [1], and their cooling demand is increasing. Global residential space cooling demand was estimated to be about 300 TWh in 2000, and it is expected to rise up to 4000 TWh in 2050 and 10,000 TWh in 2100 [2]. According to different prognoses, in European Union (EU) countries the cooling demand will increase of almost 60% in 2030 respect to nowadays [3,4]. These statistics are even more valid in regions with tropical climates [5]. For instance, the percentage of energy used for space cooling in Mumbai (40%) is nearly as twice as that of London (20%) [6].

Providing cooling in an efficient way is harder than providing heat because the cooling demand is more difficult to predict than the heat demand, particularly the peaks [4]. Cooling demand, in fact, depends on different factors that can change quickly, such as solar radiation, internal heat gains, and the urban heat island effect [3]. Moreover, due to the increasing renewable energy source (RES) share, the stability of the electricity grid is at risk [7]. RESs such as wind and solar energy are intermittent, therefore they cannot be easily controlled and predicted. For this reason, it is harder and harder to keep the balance between generation and use of electricity, with an associated increasing risk of black-outs and other technical issues. Given all the aforementioned reasons, it is fundamental developing more efficient cooling systems to improve the sustainability of future cities.

Cooling demand can be met using individual solutions (air-conditioning split systems, or more efficient solutions such as absorption cycles and electric chillers), or using one solution for the whole building or cluster of buildings [5]. In this last case, district cooling systems (DCSs) represent an example of efficient means to fulfill the cooling demand [5]. A DCS can be considered as a centralized method of cold thermal energy production and distribution for space and process cooling. A typical DCS includes the following elements: a central generation unit, a distribution network, customers and a heat rejection system. Given its cost-effectiveness, chilled water is often used as heat transfer fluid.

The EU Energy Efficiency Directive [8] has stated that DCSs are one of the important pillars for achieving the energy efficiency target of reducing primary energy consumption by 20%, while the Strategic Energy Technologies Information System (SETIS) [9] has recognized DCS as Best Available Technology (BAT) for the cooling market in the EU. Moreover, the Heat Roadmap Europe [10,11] considers thermal networks (which include DCSs) to be fundamental to increase energy efficiency. Current yearly district cold deliveries can be estimated to be around 300 PJ worldwide (200 PJ in the Middle East, 80 PJ in the USA, 14 PJ in Japan, 10 PJ in Europe) and, in particular in Europe, there are around 150 systems in operation [12].

DCSs are becoming increasingly popular in the areas with high density of buildings, because of their high efficiency and flexibility [13]. However, literature on DCSs is limited because district cooling development has been more recent respect to district heating. Moreover, it has to be considered that the temperature difference between the supply water temperature and the return water temperature for DCSs is usually around 8 °C, while in district heating systems the difference is generally higher than 40 °C [3]. Additionally, the tendency to be cautious in the design phase leads often to oversize DCSs, thus resulting in equipment underutilization, which is detrimental for energy efficiency [6]. For all these reasons, DCSs show an increase of the piping system cost and of the required pumping energy respect to district heating systems [3]. Therefore, the amount of cold supplied by DCSs in the world is much smaller than heat supplied by district heating systems [12].

DCSs can be successfully integrated with RESs, trigeneration systems and thermal storage systems (TESs). Renewable energy resources include solar energy, wind energy, geothermal energy, biomasses, energy from the surface water (sea, rivers, lakes), etc. The integration of DCSs with renewable energy technologies allows reducing greenhouse gas emissions greatly [13]. DCSs using solar energy can be exploited in absorption refrigerating cycles [14]. Systems coupling DCSs and geothermal sources are mainly connected to aquifers or groundwater [13,15,16], while biomasses are generally based on municipal solid waste whose incineration and consequent heat is recovered for absorption chillers [13,17]. Surface water systems are frequently used in DCSs, using as cold source seawater heat pumps [18,19], river water [20], and deep lake water [21].

DCSs integrated with trigeneration systems, instead, have the possibility of improving the fuel energy efficiency, and are generally coupled with district heating systems to meet the heating and cooling demand of the users. Often, the DCS serves as a supplemental system to meet the cooling demand of the area [22], and thermal driven chillers are generally used to recover low grade heat from the trigeneration system [13]. Applications of single DCSs coupled with trigeneration systems are rarely reported, probably because the trigeneration energy efficiency is not high when the primary aim is to meet the cooling demand [13].

When integrated with TESs, DCSs energy consumption and operation cost at peak hours can be considerably reduced. TESs are able to store cold energy during periods of low cooling demand, and the stored energy can be used later to meet the required cooling load. In this way, the utilities benefit from the reduction of the peak electricity generation and consumers can take advantage of lower billing charges [13]. Typical TESs used in DCSs include chilled water, ice and phase change materials. Chilled water is generally used in its sensible form and its advantages result in low cost and high thermal capacity. Ice, instead, is used in form of latent heat, and is generally chosen when smaller storage volumes are required. Phase change materials (PCMs) adopted in DCSs usually include inorganic salt hydrates and paraffins. Salt hydrates have high latent heat during solidification/melting and are low-cost, but they can show incongruent melting and corrosion issues. Paraffins, on the other hand, can result in very high cost [13].

Another possible source rather than RES for DCSs is waste cold energy, which can be recovered from industry, commercial, and transport sectors [23]. While solar, geothermal and biomass waste energy are not as used as in district heating systems because of poor efficiencies due to energy conversion [13], liquefied natural gas (LNG) is in this study considered as a suitable source for DCSs. LNG is widely used to transport natural gas, especially when the distance between the production site and the market is longer than 2000 km [24]. LNG is obtained by cooling natural gas to −162 °C at atmospheric pressure; one cubic meter of LNG contains around 600 cubic meters of natural gas, making the energy density of LNG significantly higher [25]. Before being sent to the customers, LNG is re-gasified and a large quantity of cold energy can be released. A typical liquefaction process requires around 2900 kJ kg^{-1} of energy; of this amount, 2070 kJ kg^{-1} are dissipated as heat, while 830 kJ kg^{-1} are stored in LNG as cold [26]. LNG can also be used as vehicle fuel in its liquid form or re-gasified to be used as compressed natural gas (CNG). In the latter case, the liquid to compressed natural gas (L–CNG) refueling station has higher efficiency than traditional CNG refueling stations [27].

In these peculiar fuel stations, natural gas is stored in its liquid form and the CNG to refuel vehicles is obtained from LNG vaporization. The LNG is typically stored in a low-pressure cryogenic tank and then pumped with a cryogenic pump to increase the pressure of LNG up to the CNG pressure. Then, a high-pressure atmospheric vaporizer converts LNG into CNG, stored in pressurized cylinders. L–CNG refueling plants present a number of advantages: (i) the possibility to distribute CNG when no grid is available nearby; (ii) a higher fuel purity, since LNG is already purified at the liquefaction stage; (iii) a reduced operational cost compared to a standard compressor solution, thanks to the power saving from the LNG pumping; (iv) the possibility to supply also directly LNG to vehicles using it as fuel [28].

Nowadays, in Italy there are 53 LNG and CNG refueling stations powered by LNG [29]. Among these, 13 are L–CNG plants [30]. In these plants, the LNG vaporizer is typically a high-pressure atmospheric heat exchanger. Looking to the data on the CNG annual consumption for the automotive sector, a great waste of cold energy can be estimated when LNG is vaporized. Data available for 2015 reports an Italian LNG demand from L–CNG refueling stations of about 5400 t [31], thus about 1245 MWh year^{-1} of cold energy could be recovered from such plants.

Based on the knowledge of the authors, in literature there is no study of DSCs using waste cold energy derived from L–CNG refueling stations. Thus, in order to limit environment warming and to maximize energy efficiency, this work aims to evaluate the potential of such cold energy recovery to meet a residential district cooling demand. Since the cooling potential of vaporized L–CNG represents a free cooling source, its efficient exploitation has the possibility to greatly reduce the electric demand of the air-conditioning sector. Furthermore, the combined presence in the urban environment of residential and transport sectors highlights the potential benefits of their optimized integration.

The manuscript is structured as follows: Section 2 presents the case study considered and the description of the DCS design method. Section 3 describes the results of the study and tries to highlight the potential of the coupling in terms of electricity saving, taking as a baseline the same residential neighborhood satisfied with independent cooling systems. Finally, the main conclusions of the work are reported in Section 4.

2. Case Study

In this section, an application case is presented in which the cooling energy requirement of a residential neighborhood is satisfied with a DCS that uses the cold energy coming from a L–CNG refueling plant vaporizer (Figure 1). The following subsections provide the description of the cooling supply side and of the DC plant.

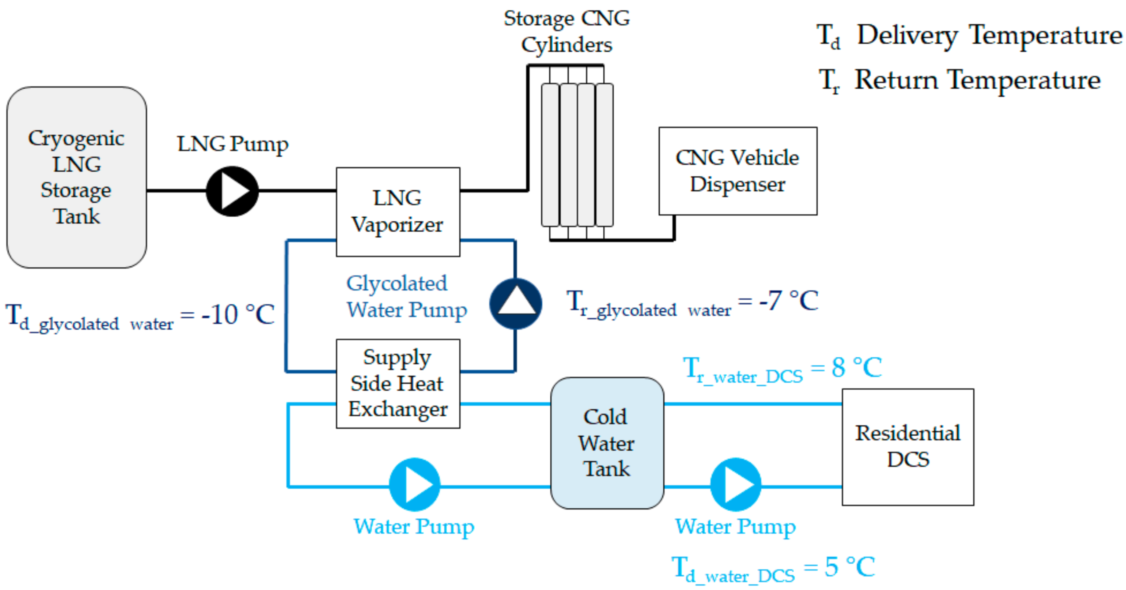


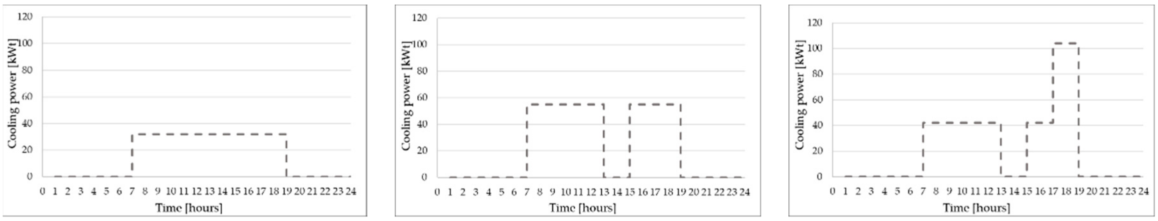
Figure 1. Plant scheme: cooling energy recovery from liquid to compressed natural gas (L–CNG) vaporizer to fulfil a residential district cooling systems (DCS) (focus on the cooling supply side).

2.1. L–CNG Cold Supply Side

To estimate the potential daily availability of recoverable cold energy from a L–CNG plant in a refueling station, data of CNG end-uses in Italy were considered. Franci [31] reports that the LNG consumption for the automotive sector in L–CNG plants is about 5400 t year^{-1}. Given such annual LNG consumption and assuming a quantity of energy of about 830 kJ kg^{-1} of LNG wasted during the LNG regasification process [26], about 380 kWh$_t$ day^{-1} of cold energy can be recovered if the fuel station is in operation every day of the year (i.e., 365 days per year); excluding the weekends the amount could result in about 550 kWh$_t$ day^{-1} (i.e., 253 days per year).

To evaluate the DCS capability to adapt its demand to the supply, the available cold energy is provided to the DCS by means of three different daily cooling power profiles (Figure 2). In the first case (Figure 2a, P1), the cooling power is constant and available 10 h a day, for every day of the year. This situation describes the typical opening and closing times of the Italian fuel stations, which were assumed to be from 7 a.m. to 7 p.m., and represents the simplest condition for the DC plant. Considering that in Italy many CNG fuel stations are closed during lunch time and weekends, another cooling power profile was considered accordingly in Figure 2b (P2). The last case, shown in Figure 2c (P3), introduces a variable profile with a peak power in the evening. In fact, as Farzaneh-Gord et al. [32] highlighted in their analysis by monitoring the number of refueling CNG vehicles in a day, a peak is generally observed between 6 and 7 p.m. This last scenario is therefore introduced to consider a variable cooling power during the day.

In the three profiles, the cooling power values were calculated by dividing the daily cold energy availability for the time during which the refueling station is supposed to be open. In the last case (P3), the peak size was chosen to satisfy the peak of the users' demand (about 100 kW$_t$, as explained in Section 2.2.2), while the cooling power in the other hours was determined by a constant distribution of the remaining daily cold energy.



(**a**) (**b**) (**c**)

Figure 2. Daily cooling power recovery from a L–CNG fuel station. (**a**): constant profile for a station working every day of the year (P1); (**b**): constant profile for a station not working during weekends and stopping during lunch time (P2); (**c**): variable profile for a station not working during weekends and stopping during lunch time (P3).

The cooling power is supplied to the DCS by means of a heat exchanger ("supply side heat exchanger" in Figure 1). The heat transfer between the LNG and the water glycol was not directly modeled, but the free cooling is considered carried by a heat transfer fluid (water glycol mixture) supposed available at a temperature of −10 °C. The corresponding mass flow rate of the mixture was determined assuming an average temperature difference of 3 °C.

2.2. Residential District Model

A hypothetical residential neighborhood, located in Rome, Italy (41°55′ N, 12°31′ E), was modeled in TRNSYS [33]. To include the variability of external climatic conditions, a Meteonorm weather file was used. The number of users to be connected to the DCS has been determined through an estimation of the users' daily cooling energy requirements. Then, the minimum number of buildings whose base cooling demand is covered by the daily availability of free cooling was selected. This choice was made to ensure the maximum utilization of the free cooling.

The following Section 2.2.1 reports the details of the single user, while in Section 2.2.2 the DC plant sizing is explained.

2.2.1. Single User

The single user was modeled with Type 88 of TRNSYS. It is composed of a single thermal zone with a simple lumped capacitance structure. The main features of the envelope were extrapolated from TABULA Project [34] and a single-family house (SFH) building with the most recent construction year class (buildings built from 2006 onwards) was chosen as reference building. In the simulation model, however, only global data are required as input; thus, an overall building loss coefficient, which considers the different thermal characteristics and dimensions of opaque and transparent envelope components, was calculated (0.38 W m^{-2} K^{-1}). The single building is composed of two floors and has a living area of 160 m^2 (80 m^2 per floor). Based on the data reported in [34], for each external wall, 8% of window surface area rate was considered.

The modeled thermal gains are: (i) solar radiation, (ii) artificial lighting and (iii) occupants' gains. Solar radiation was provided as internal gain to Type 88 and was modeled starting from the total tilted surface radiation data for each building surface orientation. Then, the thermal power due to solar radiation actually entering the building was calculated and implemented according to the procedure reported in the Italian standard UNI TS 11300:1 [35]. Artificial lighting accounts for a power density of 5 W m^{-2} and it was assumed reasonably that 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}. As concerns the occupants' contribution, an occupancy density of 40 m^2 per person with a corresponding internal gain of 110 W per person was considered [36]. The contribution of natural ventilation was introduced, too, assuming air changes per hour equal to 0.5 h^{-1} [35].

The design peak cooling demand was evaluated by means of the Carrier-Pizzetti technical dynamic method [37,38]. This method allows estimating the summer thermal load (sensible and latent contribution) at different hours of the day, having as inputs the geographical coordinates, the envelope properties (mass and thermal transmittance) and the maximum external temperature: the maximum value was assumed as peak cooling demand. For Rome, where the outside design temperature suggested by [39] is 34 °C with a daily temperature variation of 11 °C, a sensible thermal load of 6.3 kW_t was calculated (an internal temperature and relative humidity of 26 °C and 50%, respectively, were used for the assessment). The latent contribution is equal to about 2 kW_t.

The single user cooling distribution system comprises fan coil units (FCUs) modeled with Type 996, and water was considered as heat transfer fluid. Cold water is supplied at a temperature of about 10 °C, with a design temperature difference between delivery and return of 5 °C [40]. The control strategy aims to maintain the internal temperature set-point 24 h per day.

2.2.2. DCS Plant Sizing

From the energy simulation of the single user cooling demand for the main summer months (July and August [39]), a base cooling demand of about 40 kWh_t was obtained. Therefore, to ensure that the cooling energy released by the L–CNG vaporizer can always satisfy the district base demand (Figure 3), it was calculated that 14 users (with the same demand) have to be connected to the DCS.

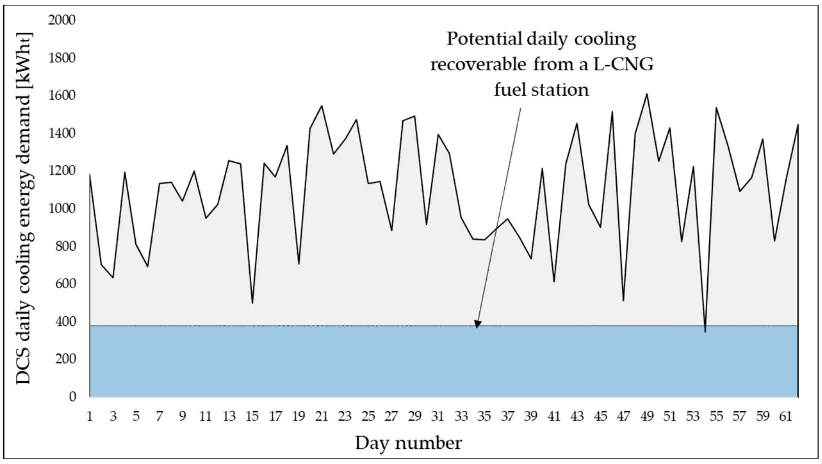


Figure 3. District daily cooling energy demand (July and August).

In order to cover higher energy demands or to cool buildings on days when there is no free cooling availability, every user was equipped with a backup system. The system includes a reversible air-to-water heat pump connected to the fan coils water circuit. The single heat pump is activated in cooling mode when the indoor temperature set-point goes above 26 °C: it integrates the energy removal when the DCS cooling power is not enough, and it meets all the cooling when no free-cooling is available.

Since there may be days in which there is no cold availability from the network (e.g., weekends), the heat pumps were sized to cover the entire design sensible cooling load (6.3 kW_t for each user, 88.2 kW_t for the overall neighborhood). Type 941 was used to model the backup system and its performance was derived from a manufacturer catalogue [41]. Figure 4 depicts, in a schematic way, how the backup system is connected to the user distribution system. The figure also shows the connection between the water fan coil units circuit and the DCS. The connection is realized with a heat exchanger modeled as a simple constant effectiveness device (Type 91 in TRNSYS, which adopts the ε-NTU method). To uncouple the cooling demand from the supply, a sensible thermal energy storage (TES) was also introduced and modeled through Type 4 as a stratified cold-water tank. Different sizes of the tank were tested, in order to find the storage that guarantees the required cold energy at the design cooling load for different periods of time.

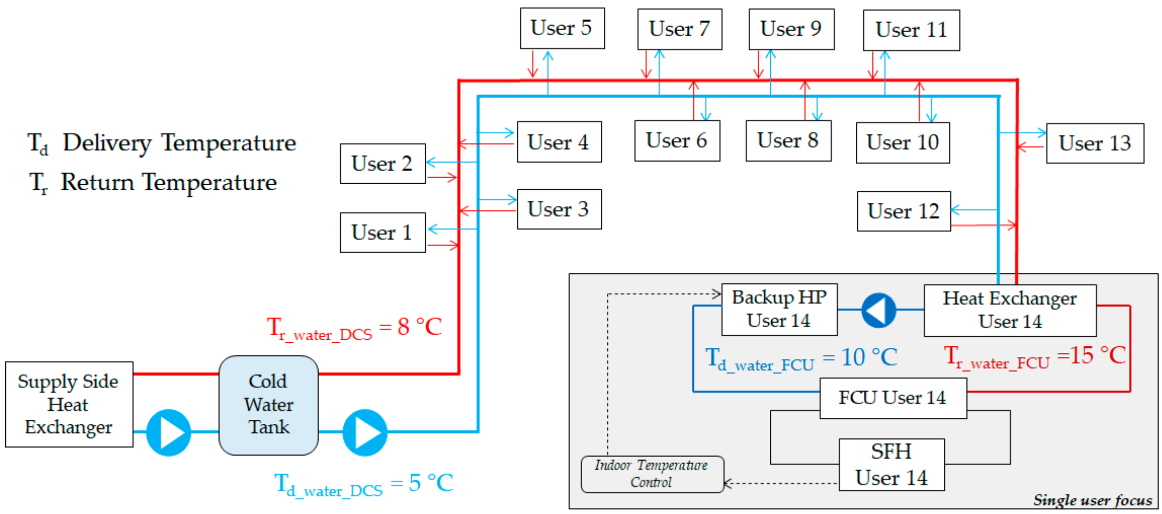


Figure 4. Residential district cooling network scheme (see Figure 1 for the details of the supply side). Focus on a single user configuration.

In the DCS, water was used as heat transfer fluid. It is delivered from the tank at a temperature of 5 °C, with a design temperature difference between supply and return of 3 °C. This choice was made to allow an efficient heat transfer between the working fluids at the single user heat exchanger, where FCUs are designed to be supplied at 10 °C (see Section 2.2.1).

The pipes were modeled as underground types (ground temperature of 14 °C) with Type 31. Referring to real pipes used for district heating and cooling systems [42], larger thicknesses (26–28 cm) of thermal insulation based on polyurethane rigid foam (thermal conductivity of 0.027 W m^{-1} K^{-1}) were considered to minimize the ground cooling energy losses. The sizing of the various DCS sections was realized maintaining the water circulation speed between 1.5 and 2 m s^{-1} in the main sections, and around 1 m s^{-1} in the secondary branches [40].

3. Results and Discussion

In this section, the simulation results of the coupling between the DCS and the L–CNG vaporizer are discussed. A reference case is introduced to evaluate the energy performance of the application. The reference case is represented by the same residential district in case of separate cooling systems: fan coil units powered by the same heat pump used for the backup cooling. From the energy simulation for the summer warmer months (July and August [39]), a total cold energy requirement of about 47 MWh_t and an electrical consumption of about 17 MWh_e were determined.

The first analysis evaluates the capability of the DCS to adapt its cooling demand to the free cooling power availability. A preliminary case, in which the DCS is directly connected to the supply side heat exchanger (without the thermal energy storage), was evaluated and the three profiles of free cooling power reported in Figure 2 were applied to the supply side.

In general, results show that the case study has a great energy recovery potential. Figure 5 represents how the users' cooling energy requirements are satisfied during the warmer summer months in case of different free cooling power profiles. In all cases the coverage of the buildings cooling demand exceeds 49%. However, although in a slight way, the shape of the free cooling profile seems to influence the district energy behavior. If the DCS is supplied with a constant cooling power profile (P1) every day, 50% of the user cooling demand is covered by the DCS itself and the electricity consumption is reduced by 52% compared to the reference case. With the increasing of the free cooling power capability (profile P2) during weekdays, a better exploitation of the cold energy provided by the DCS is obtained and the electricity saving becomes 58%. Introducing a most variable cooling power profile (P3) this improvement seems to be mitigated. Due to the daily mismatch between the cooling demand and supply, the P3 higher cooling peak power cannot be well exploited. Figure 6 shows the typical daily cooling demand of the district in the reference case. The thermal power demand starts around 10.00 a.m., when the P3 power availability is indeed low, and stays constant for several hours.

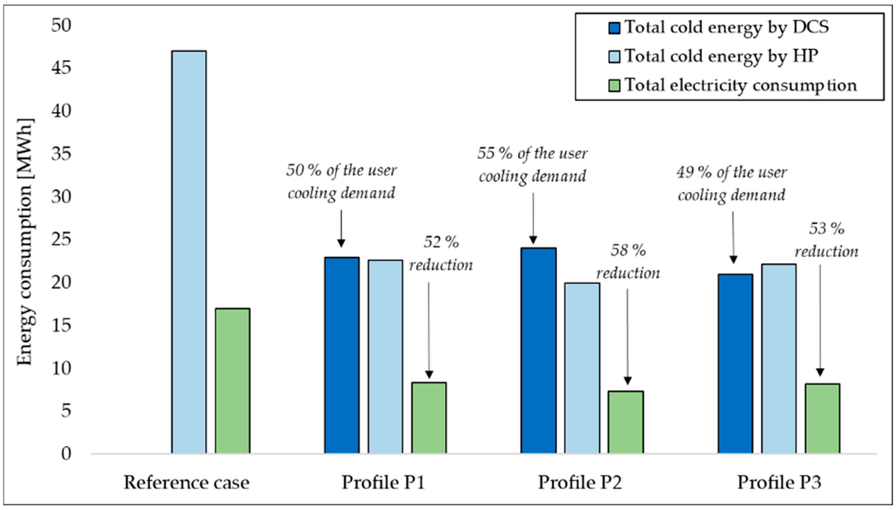


Figure 5. Total district electric consumption and users' cold energy demand divided into the share provided by DCS and by the backup systems (i.e., HP) with different free cooling power profile (months of July and August).

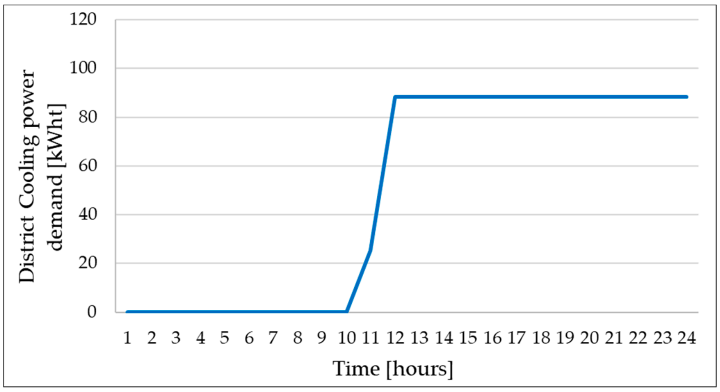


Figure 6. Total daily district cooling power demand in the reference case.

Therefore, it is evident that to minimize the electricity used for backup systems, a sufficiently high and continuous free cooling power is beneficial (i.e., P2). The effect of the introduction of a certain level of thermal inertia at the demand side is investigated in order to evaluate if it helps to decouple the cooling demand and the supply both in terms of time and of peak power potential. The installation of a tank of 60 m^3, which in design conditions can provide the users' peak power demand (about 88 kW) for 1 hour with a temperature difference of 3 °C, is considered. Figure 7 shows how the users' cooling energy requirements are satisfied during the warmer summer months in case of different free cooling power profiles when the TES is introduced at the demand side. Comparing them to the data shown in Figure 5, a good increase in the DCS energy performance can be noticed in case of P3 profile: the seasonal demand covered by the DCS goes up to 59% with an electricity consumption reduction of about 60% compared to the reference case. For the other two cases (P1 and P2), the storage has practically no contribution, being their trend much more regular.

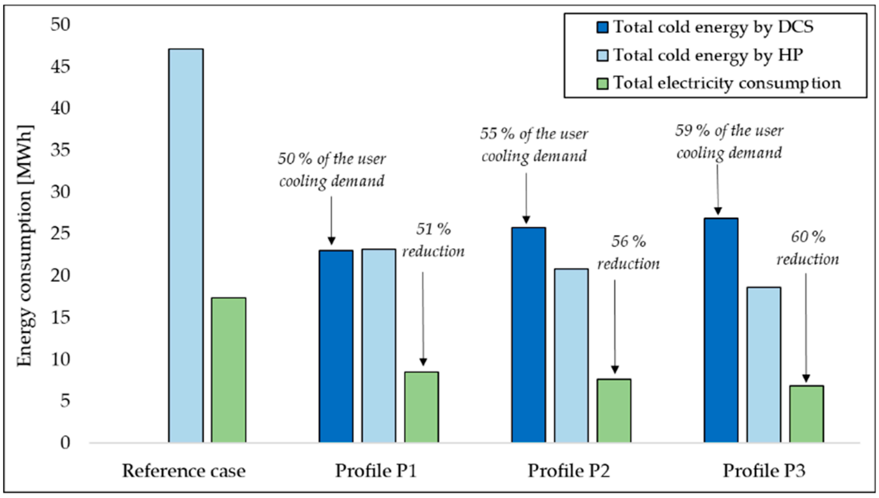


Figure 7. Total district electric consumption and users' cold energy demand divided into the share provided by DCS and by the backup systems (i.e., HP) with different free cooling power profile (months of July and August) in presence of a cold-water tank of 60 m^3.

The addition of a TES allows a better daily balance of energy demand and supply, too. Figure 8 shows for a typical summer day how the total cooling demand is satisfied when the free cooling availability is directly connected to the demand (Figure 8a) or decupled with a 60 m^3 TES (Figure 8b). Without the TES, the users have to switch on the backup systems from 5 p.m. onwards to maintain the temperature set-point, while in presence of the TES the backup systems do not switch on because more cooling power is available thanks to the stored energy.

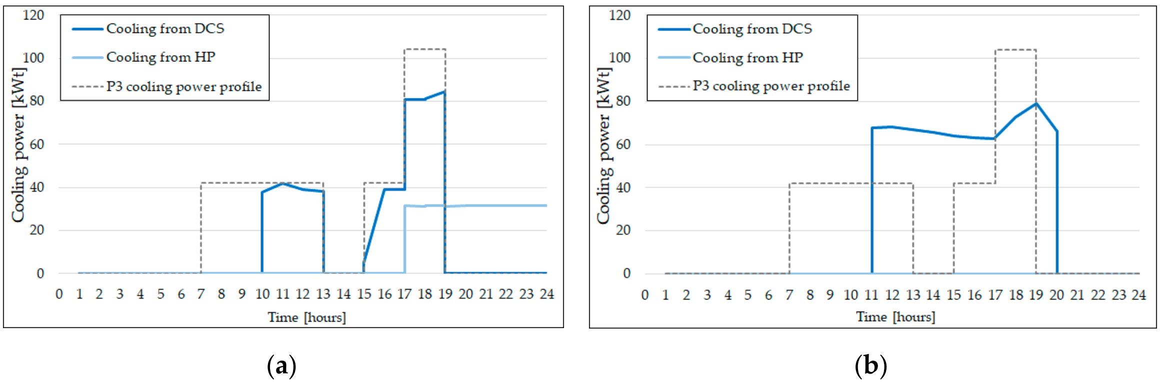


Figure 8. Daily cooling demand breakdown into the DCS and HP share in case of cooling supply profile P3: (**a**) without a TES; (**b**) in presence of a cold-water tank of 60 m^3.

Even though in the analyzed case the use of a thermal storage allows a higher level of energy recovery with higher electricity saving, in the DC plant sizing special attention must be paid to the choice of the tank volume. Tanks too small or too large, in fact, could cause performance degradation. Figure 9 reports the cold energy recovery from the L–CNG vaporizer compared to the global cooling demand and the percentage of electricity saving for different volumes of the TES (P3 profile). The best energy performance was obtained for tanks with a size between 30 and 90 m^3. Lower values do not provide enough level of thermal inertia, while higher values seem to slow down the dynamics of the system too much. In fact, if the tank is empty and the cooling power demand is at its peak, the large thermal inertia introduced by the tank prevents from satisfying the demand because the TES has to be first recharged; therefore, backup systems need to be switched on. Moreover, increasing the size of the tank enlarges the heat losses towards the environment, thus resulting in an energy efficiency penalization of the system.

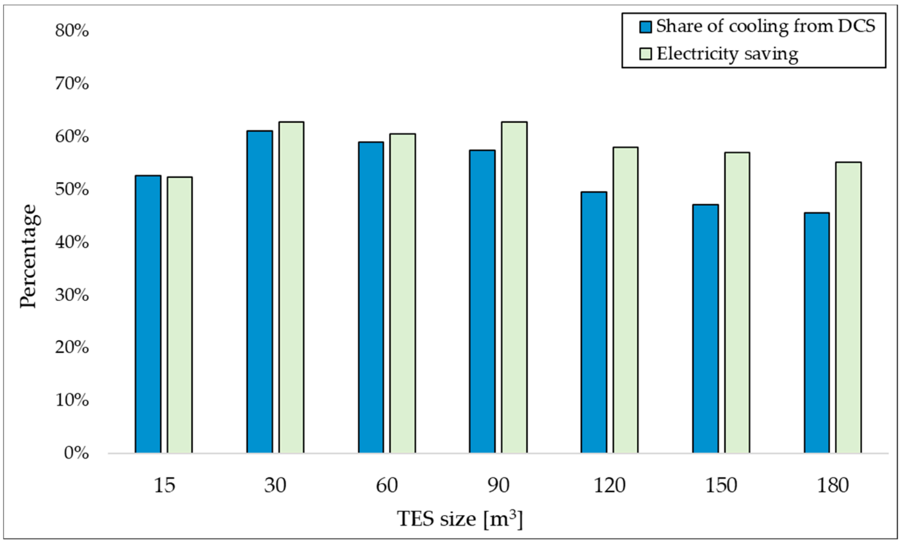


Figure 9. Percentage share of cooling from DCS to meet the total users' demand and electricity saving for different thermal energy storage (TES) sizes.

4. Conclusions

The present study provided an overview of advantages, issues and potential applications of district cooling systems (DCSs). DCSs can deliver cold energy supply at low cost and with low carbon dioxide emissions, and can be integrated with renewable energy systems, trigeneration systems and thermal energy storages. They can also recover efficiently waste cold energy from applications such as liquid to compressed natural gas (L–CNG) refueling, technology that was considered as a case study in this work.

Specifically, an energy system comprising a L–CNG refueling station vaporizing LNG to meet the space cooling demand of a small residential neighborhood was designed and modeled in a dynamic simulation environment. Results show that the DCS is able to provide high electricity saving levels in comparison with the baseline case, in which standard cooling systems are installed in every building. Regardless of the supply cooling power profile, electricity consumption reductions greater than 50% were obtained, reaching 60% in the best scenario (profile P3 with a 60 m^3 thermal energy storage at the demand side). It is necessary to highlight that these percentages are strongly dependent on the assumptions made to design the DCS, having assumed the cold energy availability from the LNG vaporizer as the district energy base demand. Further investigations should be conducted to evaluate the impact of the DCS sizing method used to select the number of users to be connected and to maximize the exploitation of the free cooling source.

To conclude, this work highlights that cold energy recovery from liquified natural gas vaporization in refueling stations can be effectively used to supply a residential DCS. Furthermore, since both the transport and the residential sector are included into the urban environment, the potential benefits of this integrated system are evident.

Author Contributions: Conceptualization, A.A.; methodology, A.M. and G.C.; validation, A.M.; writing—original draft preparation, A.M. and G.C.; writing—review and editing, G.C.; supervision, A.A. and F.P.; funding acquisition, F.P.

Funding: This research was funded by the Italian Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR) within the framework of PRIN2015 project "Clean Heating and Cooling Technologies for an Energy Efficient Smart Grid", Prot. 2015M8S2PA.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

BAT	Best available technology
CNG	Compressed natural gas
DCS	District cooling system
EU	European Union
FCU	Fan coil unit
HP	Heat pump
L–CNG	Liquid to compressed natural gas
LNG	Liquefied natural gas
P	Cooling power profile
PCM	Phase change material
RES	Renewable energy source
SETIS	Strategic Energy Technologies Information System
SFH	Single-family house
TES	Thermal energy storage

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