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Optimization of Solar District Heating & Cooling Systems

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Optimization of Solar District Heating & Cooling Systems

G. Brumana[1], G. Franchini[1], E. Ghirardi[1] and S. Ravelli[1]

[1]Department of Engineering and Applied Sciences, University of Bergamo, 5 Marconi Street, Dalmine 24044, Italy

E-mail: giovanni.brumana@unibg.it

Abstract. The present work proposes a comparison between three solar-powered district heating and cooling systems, namely: 1) centralized district heating & cooling (DHC) system; 2) 5th-generation district heating & cooling (5GDHC) system and 3) individual AC plants (HHC, Home Heating and Cooling), in different climate conditions. Thermal loads are evaluated by transient simulations of a residential compound featuring 56 detached houses for three different Italian climates: (1) a Mediterranean region on the seaside (Palermo, I), (2) a temperate climate in Central Italy (Roma, I), and (3) a cold-temperate climate in Northern Italy (Bolzano, I). The DHC system shows the highest efficiency in terms of energy-savings, whatever the location. The 5GDHC system reaches a compromise between installation and operational costs.

1. Introduction

Air conditioning is a major contributor to the increase in global greenhouse gas emissions [1], and the focus of many studies is on developing more efficient energy distribution systems to reduce the environmental impact. A promising solution is the adoption of district systems with a considerable improvement in terms of energy savings, especially for new green city project [2]. The 4th generation centralized district system is the most common option (DC) [3] even though in recent years the emerging 5th generation district heating and cooling (5GDHC) has proven to be the best solution for temperate climate due to a low expensive infrastructure, with respect to the standard solution, coupled with a high-efficiency reversible heat pump [4].

With the aim of reducing fossil fuel exploitation, the adoption of renewable-based solutions forces the market to introduce new and more efficient ways to drive the air condition system with green energy. District systems and home solutions could be converted into fossil-free plants provided that detailed study and optimization [5] are carried out to achieve a high level of reliability. The adoption of renewables as energy sources highlights the importance of having a system with good performance and overlap between load and solar irradiance, especially with cooling demand [6]. The market trend awards the combination of compression chiller with photovoltaic fields [7] because of easy integration in the existing grid infrastructure. In addition, as part of the EU roadmap, the Italian government has planned to increase the level of integration of renewable sources in the energy sector. To do this, the use of storage systems is crucial to mitigate power fluctuations thus ensuring stable and reliable supply of energy [8]. However, it must be kept in mind that the large-scale deployment of electric energy storage systems, in the form of lithium-ion batteries, is gradually playing a very relevant role within electric networks despite being not economically viable: the overall cost is about 325 USD/kWh [9] with a cell cost of 176 USD/kWh [10].

The design procedure of a district system requires a complex evaluation [11] and detailed transient simulations as reported by Wang in [12] and by Oppelt et al. in [13]. The large number of variables included in numerical models forces the adoption of optimization procedures [14].

Starting from previous works carried out by the authors in that field [15] [16] this study deals with a complete model of a conditioning system driven by renewable sources for a new residential compound. The setup includes the evaluation of building heating and cooling load, operation and performance of the district system coupled with a photovoltaic field, battery storage, and the plant operation based on reversible heat pumps. The procedure, based on transient annual simulation, performs a detailed optimization delivering the best techno-economic solution among three available solar-driven technologies: 1) centralized district heating & cooling (DHC) system; 2) 5th-generation district heating & cooling (5GDHC) system and 3) individual AC plants (HHC).

2. Residential compound demand

To provide a complete assessment of solar heating and cooling solutions for a residential compound, the modelling procedure was divided into two sub-sections: the residential compound and the heating and cooling plant coupled with the district network (for DHC and 5GDHC).

The evaluation took into account three different locations across the Italian land: Bolzano, Roma, and Palermo. A summary of ambient conditions is reported: profiles of temperature and radiation shown in figure 1 and in figure 2, respectively, derive from the Meteonorm database [17].

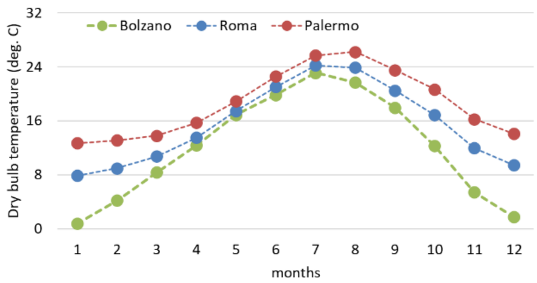

Figure 1. Monthly average temperature

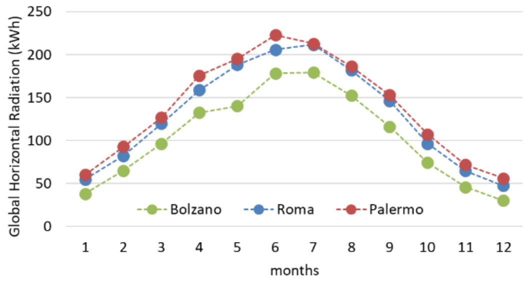

Figure 2. Global horizontal radiation

The conditioning requirements of a residential compound of 56 single villa has been modeled using the software Trnsys 18 [18] coupled with Trnsys3D plug-in [19], starting from the real geometry of a two-floor 550 m^2 house and considering occupancy, lights, and appliances. The total heating and cooling demand of each single building derives from a transient annual simulation consistently with the procedure reported in [20]. Annual values of heating and cooling load, in terms of sensible and latent energy, are collected in Table 1.

Table 1. Building annual heating and cooling load (kWh).

	Bolzano	**Roma**	**Palermo**
Heating load	66336	35719	16464
Sensible cooling load	9538	14739	23614
Latent cooling load	9959	19643	31049
Global cooling load	19497	34382	54663

3. Solar-assisted conditioning systems

The energy source is based on a photovoltaic system coupled with Li-Ion batteries devoted to store any overproduction, according to their power limit and maximum capacity. However, the air conditioning system is grid-connected to feed back any excess energy and to meet the load in case PV and battery are not self-sufficient. The models of PV modules and batteries are the same for all the three layouts and the main parameters are listed in Table 2.

Table 2. Solar fields and battery storage specifications

Solar Field (PV)			Battery storage		
Maximum power (Pmax)	W	375	Total Energy	kWh	14
Module efficiency (ηm)	%	20.1	Usable Energy	kWh	13.5
Temperature coefficient Isc	%/°C	0.044	Apparent Power, max continuous	kVA	5.8
Temperature coefficient Uoc	%/°C	-0.275	Power Factor Range	-	0.85
Temperature coefficient Pmpp	%/°C	-0.350	Round Trip Efficiency	%	90

3.1. District heating and cooling (DHC)

The cooling load of the single building was adopted as input for the district simulation in a deep transient analysis considering peak shaving effects and thermal dissipation in the network as described in [15]. The piping design parameters, taken from the technical literature [21], include an insulation thickness equal to 5 cm and a design water speed of 2.75 m/s, according to suggested best practice [22] [23]. The district network layout prescribes 2 pipes for cold distribution and 2 pipes for hot distribution. The heat transfer substation, with a temperature difference of 7 °C, provides heating and cooling to the users.

The energy plants rely on a centralized industrial-grade reversible heat pump that provides hot water and chilled water streams. The main specifications of the system are shown in Table 3. The COP values, which refer to a 1 MW unit, are kept constant at nominal conditions whatever the size. This because the effective sizing will come from the optimization procedure. Conversely, off-design operation is computed with respect to a performance map that considers temperature and part-load derating.

As underlined in the previous work by the authors [24], the heat rejection system is a crucial aspect of energy performance evaluation. Here, the proposed solution relies on geothermal water, with different seasonal variations and temperature levels for each of the three locations. Design temperature levels of the district system, at the pump station, were selected equal to 5 °C and 15 °C for supply and return piping, respectively

3.2. 5th generation district heating and cooling (5GDHC)

The 5th generation district heating and cooling technology is the most advanced solution for building air conditioning. The system couples the district system reliability with the user-tailored solution of the home reversible heat pump. The selected layout relies on a two rings solution with the parallel flow. Temperature levels are equal to 18 °C and 24 °C according to open literature suggestions [25]. The ring temperatures fluctuate during the year with respect to the design levels and they are stabilized with a groundwater source or centralized plant. The reversible heat pump installed in each building complies with the operating parameter of a 30-kW system; off-design operation is simulated according to a performance map provided by the manufacturer. The heat pump specifications are reported in Table 3.

3.3. Home central heating and cooling (HHC)

Moving to the home system, the single building heating and cooling loads are satisfied by a central home system based on an air-cooled high efficiency reversible heat pump. The heat pump is considered to operate in direct mode and the performance is referred to 47 kW chiller design capacity (Table 3). . The adoption of a dry cooler represents the standard solution for home applications and represents the majority of the installed systems in Italy.

Table. 3: Reversible heat pump specifications

		DHC	5GDHC	HHC
	unit	value	value	value
Design chiller capacity	kW	1000*	35*	47*
Design COP	-	5.65 (at 30 °C)	3.01(at 35 °C)	2.94 (at 35 °C)
Design power input	kW	215	7.38	7.38

* The power rating is a typical value for residential applications, for which the performance coefficients reported were defined.

4. Optimization procedure and results

All proposed air conditioning solutions have been designed to cover 70 percent of annual electrical demand through solar radiation. The selected level of solar fraction (SF) is considered a valuable target to reduce environmental impact without imposing an out-of-market installation cost [26]. The system has been optimized using the software GenOpt which runs thousand annual Trnsys simulations with the aim of minimizing an objective function [27]. The algorithm starts selecting a variables combination among a user-defined search space reported in Table 4. The procedure based on the particle swarm algorithm identifies the combination of chiller nominal capacity (Cap_{CC}), photovoltaic area (A_{PV}), and storage capacity ($Cap_{battery}$) that minimizes the installation cost (Eq. 1) achieving the desired renewable fraction, as reported in Eq. 2. The optimization function (Eq. 1) includes a penalty term ($Penalty_{(SF<0.70)}$) that forces the algorithm to reject all combinations that do not meet the RF target. The district network cost, which is not considered in the optimization being a fixed value, is accounted for in the economic analysis.

The optimization function is based on the cost of the main components, listed in Table 5. Furthermore, the reference costs are size-dependent with the aim of highlighting the differences between single-user components with respect to large systems. Sources of cost data are the following:

- from manufacturers, for both home and central reversible heat pump systems;
- from the open literature for the PV [28] [29];
- from the market analysis provided by [10] for the electric energy storage, such as a Li-Ion battery
- from the technical report by Davies [30], for the district system (station, branch, piping, users substation). It is meant as a cost per unit of user (N) connected to the network.

Table. 4: Optimization variables and related search space

		DHC	5GDHC	HHC
		min - max	min - max	min - max
Cooling Rated Capacity	kW	900 - 4000	1200 - 4000	1500 - 4000
PV field	m^2	2000 - 12000	3000 - 16000	2000 - 30000
Battery	kWh	500 - 3000	1000 - 4000	1000 - 8000

*The reported values are to be considered as referring to the whole housing complex (sum of 56 single house)

$$f_{min} = A_{PV} \cdot Cost_{PV} + Cap_{CC} \cdot Cost_{CC} + Cap_{battery} \cdot Cost_{battery} + Penalty_{(SF<0.70)} \quad \text{(eq. 1)}$$

$$SF = \frac{E_{PV} - export}{E_{heat\ pump}} = \frac{E_{heat\ pump} - import}{E_{heat\ pump}} \quad \text{(eq. 2)}$$

Table. 5: Components installation costs

		DHC	5GDHC	HHC
Chiller	USD/kW	140	500	800
Distribution network	USD/N	14000 (2·7000)	4000	0
Heat exchanger	USD/N	3000	3000	0
PV panel	USD/m^2	119.2	178.8	178.8
Battery storage	USD/kWh	328	510	510

The optimization procedure resulted in the combination of variables shown in Fig. 3, in terms of solar array opening area, storage sizing and chiller capacity rating, for the three selected locations and for each system layout. The layout based on the centralized district system requires, regardless of location, the lowest component capacity, whatever the location. The trend highlights an increase in components sizing moving from centralized DHC to home solution due to the lower efficiency of the small system in terms of COP for the reversible heat pump. Furthermore, the optimization procedure delivers a bigger heat pump capacity to compensate for temperature derating, with respect to the peak load design.

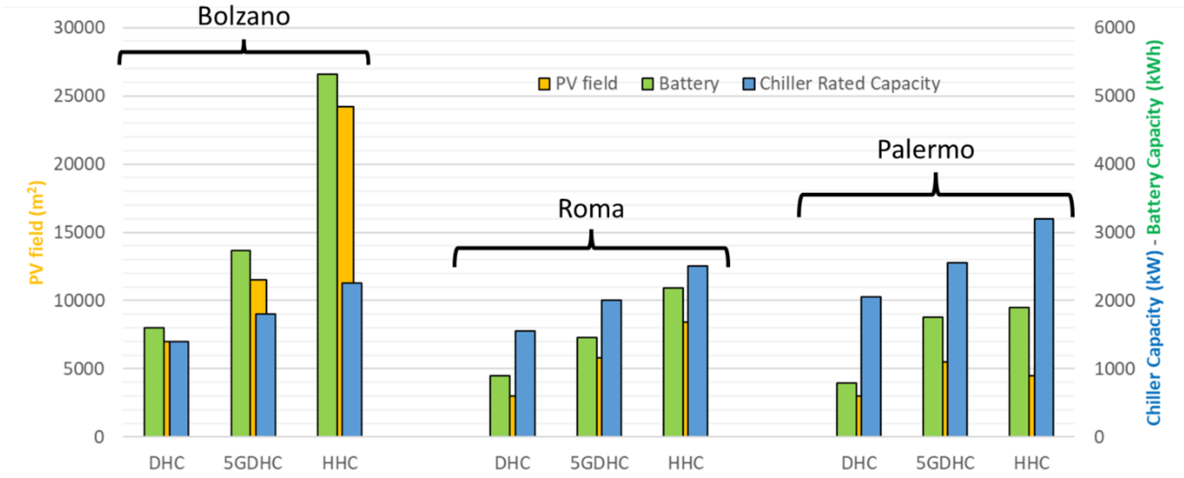

Figure 3. Optimization results: components sizing

Fig. 4 shows the rated COP reported by the manufacturer compared with the annual average COP considered as energy consumption vs. energy production (sum of heating and cooling). The figure points out that 5GDHC, compared with the centralized system, provides a better operating condition for the heat pump but, due to the smaller sizing, the COP is lower . Furthermore, the COP affects the battery operation: the centralized district system (DHC) system required a small battery pack (from 50% to 70% lower than other solutions) to achieve the same annual result.

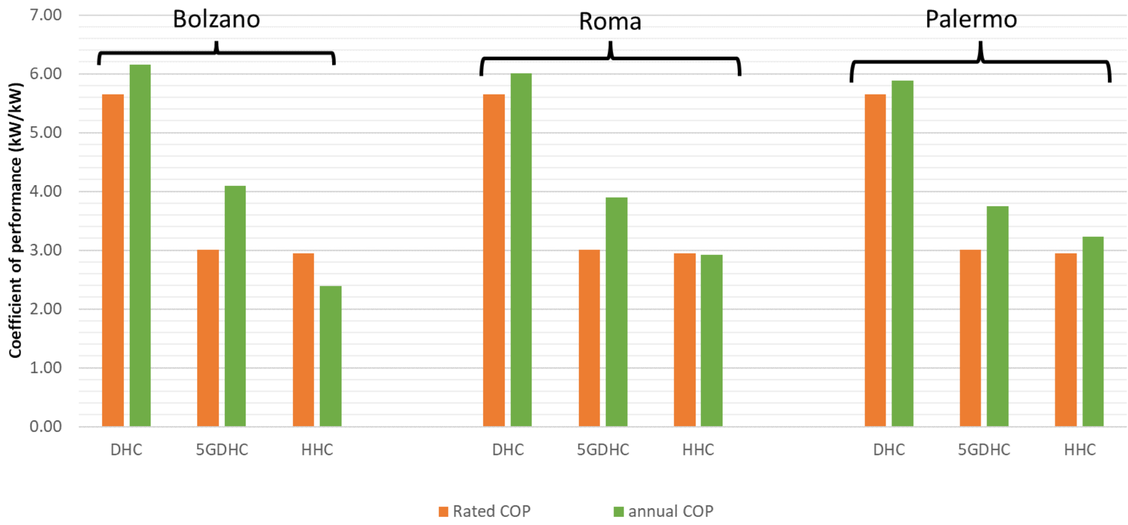

Figure 4. Heat pump rated COP and annual average COP

5. Results and discussion

The optimum combinations have been simulated for a whole year with a time-step of 7.5 min. Figures 5 and 6 show an example of the detailed simulation results for the centralized plant in Roma; specifically, the power balance trends for the fourth week of January (max heating load) and the last week of July (max cooling load) are depicted. The selected weeks represent the worst operating conditions in terms of heating and cooling load for that location. The electric load required by the chiller has been reported by a black dashed line (Eload). The photovoltaic system power production (PV – yellow line) highlights the importance of the storage charge-discharge behaviour (Battery – green line). The battery allows storing part of the daytime production to fulfil the night load operation of the chiller. Nevertheless, the system exports energy (Export – red dashed line) to the grid when the battery level reaches the maximum and imports energy (Import – blue dashed line) from the grid in case of battery depletion in the early morning. The load is completely satisfied most of the time and the annual solar cooling achieved is equal to 70%.

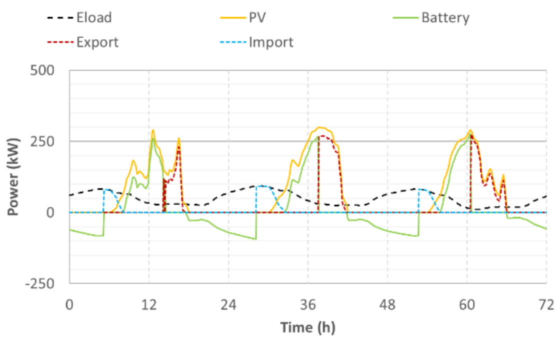

Figure 5. Three days of detailed operation of centralized solar cooling (winter)

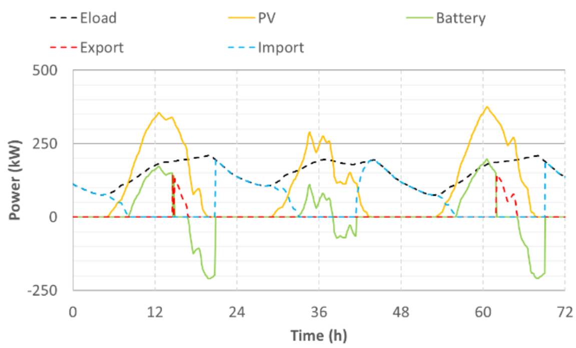

Figure 6. Three days of detailed operation of centralized solar cooling (summer)

5.1. Economic considerations

The economic analysis of the system, based on the budget costs and optimum sizing, highlights some interesting key points. Figure 7 shows the contribution of the components to the global cost in absolute terms. The energy source (PV and battery) accounts for 30% to 50% of the global cost with a large variation between different conditioning systems. The chiller cost increases moving from DHC to

HHC due to lower efficiency and the detrimental impact of the ambient conditions on the operation. The cost of district system components is much higher than for 5GCHC, due to the need for more insulation and operations to build the network branches (since DHC requires a four-pipe arrangement while 5GDHC features a two-pipe configuration). Nevertheless, the adoption of DHC is an effective solution to provide heating and cooling to the user with a relatively low installation cost.

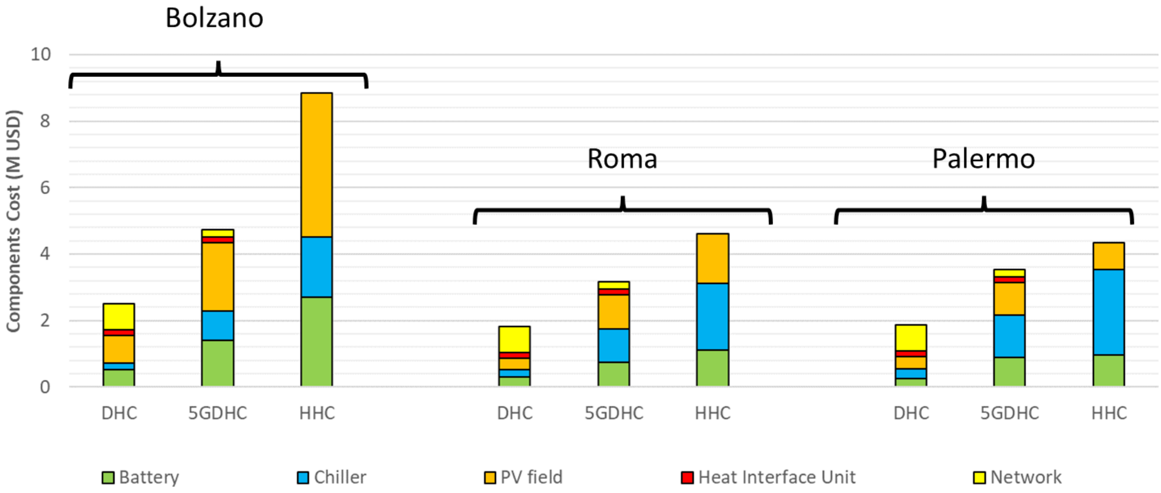

Figure 7. Economic analysis of the optimum configurations

Moving to the specific cost of thermal energy, the Levelized Cost of Thermal Energy (LCOTE) has been computed as reported in Eq. 3 according to a new approach suggested in [31]. The LCOTE is computed as the sum of a single component contribution to global thermal energy production during its service life (comparably to the Levelized Cost of Electricity evaluation approach) including the operation and maintenance costs and the energy exchanged to the grid with an electricity price of 0.30 USD/kWh.

$$LCOTE = LCOTE_{PV} + LCOTE_{Battery} + LCOTE_{DC} + LCOTE_{CC} + \frac{E_{impot-export} \cdot E_{cost}}{Qheat\ pump} \quad \text{(eq. 3)}$$

The LCOTE value in Figure 8 highlights the lowest energy cost for the district system, ranging from 0.07 USD/kWh (Bolzano) to 0.13 USD/kWh (Roma).whereas HHC costs are the highest, from 0.36 USD/kWh (Palermo) to 0.78 USD/kWh (Bolzano). 5GDHC lies in between, with costs spanning from 0.27 USD/kWh (Roma) to 0.45 USD/kWh (Bolzano). It can be noted that 5GDHC has the peculiarity to ensure the best performance in the temperate climate of Roma, when heating load is similar to cooling load. The results confirm that the lowest thermal energy cost is achieved by district systems; 5GDHC operation is cost-effective only in balanced climates.

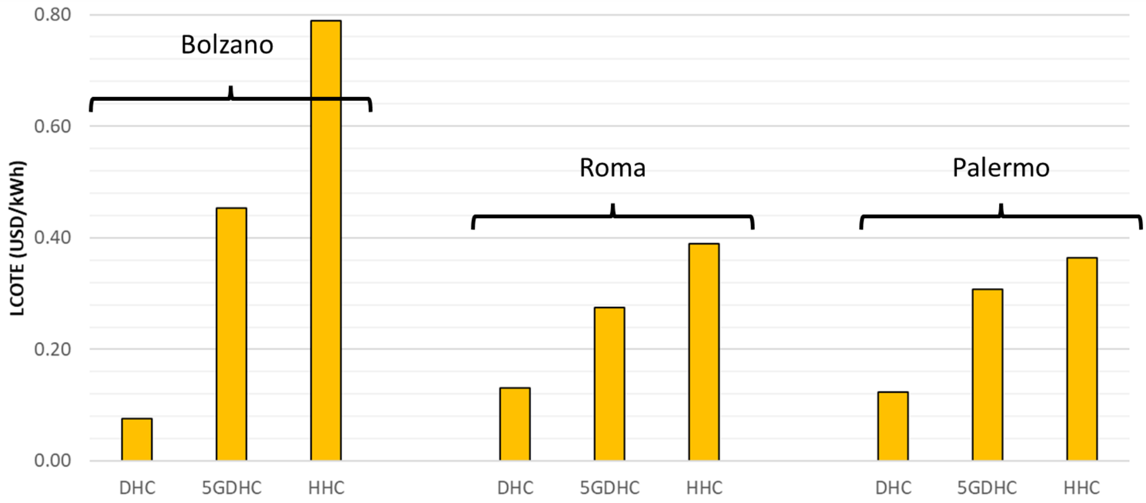

Figure 8. Economic analysis of the optimum configurations

6. Conclusions

The paper deals with a district system optimization fed by solar energy compared with the home heating and cooling system based on heat pump. The plant configurations include PV as renewable power generation, Li-ion batteries as energy storage and electric chillers. Each component was modeled according to the performance maps provided by the manufacturers thus allowing an accurate simulation in both design and off-design operating conditions. The investigation includes energy, economic and environmental aspects for three representative locations in Italy (Bolzano, Roma, and Palermo).

A multi-variable optimization procedure, based on GenOpt software interacting with Trnsys models, was used for component sizing. For every technology, the optimal configuration has been determined by minimizing the installation cost through a two-step algorithm, under the constraint of a 70% annual electric energy demand covered by solar energy.

The DHC system was found to provide the highest efficiency in terms of energy-savings even though the piping installation reduces the cost-effectiveness in the case of heating requirements. The DHC system is advantaged by a predominant heating or cooling demand whilst, on the contrary, the fifth-generation network is advantaged, as in the case of Roma, in temperate locations. Concluding, the 5GDHC system represents a suitable compromise between installation and operational costs.

References

[1] Eveloy V, Ayou DS. Sustainable district cooling systems: Status, challenges, and future opportunities, with emphasis on cooling-dominated regions. Energies 2019;12. https://doi.org/10.3390/en12020235.

[2] Lund H, Möller B, Mathiesen B V., Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35:1381–90. https://doi.org/10.1016/j.energy.2009.11.023.

[3] Perez-Mora N, Bava F, Andersen M, Bales C, Lennermo G, Nielsen C, et al. Solar district heating and cooling: A review. International Journal of Energy Research 2018;42:1419–41. https://doi.org/10.1002/er.3888.

[4] Lund H, Østergaard PA, Nielsen TB, Werner S, Thorsen JE, Gudmundsson O, et al. Perspectives on fourth and fifth generation district heating. Energy 2021;227:120520. https://doi.org/10.1016/j.energy.2021.120520.

[5] Wang H, Wang H, Zhou H, Zhu T. Modeling and optimization for hydraulic performance design in multi-source district heating with fluctuating renewables. Energy Conversion and Management 2018;156:113–29. https://doi.org/10.1016/j.enconman.2017.10.078.

[6] Inayat A, Raza M. District cooling system via renewable energy sources: A review. Renewable and Sustainable Energy Reviews 2019;107:360–73. https://doi.org/10.1016/j.rser.2019.03.023.
[7] Huang L, Zheng R. Energy and economic performance of solar cooling systems in the hot-summer and cold-winter zone. Buildings 2018;8. https://doi.org/10.3390/buildings8030037.
[8] Luerssen C, Verbois H, Gandhi O, Reindl T, Sekhar C, Cheong D. Global sensitivity and uncertainty analysis of the levelised cost of storage (LCOS) for solar-PV-powered cooling. Applied Energy 2021;286. https://doi.org/10.1016/j.apenergy.2021.116533.
[9] Fu R, Remo T, Margolis R, Fu R, Remo T, Margolis R. 2018 U . S . Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark. 2018.
[10] Goldie-Scot L. A Behind the Scenes Take on Lithium-ion Battery Prices. BloombergNEF 2019:1.
[11] Morvaj B, Evins R, Carmeliet J. Optimising urban energy systems: Simultaneous system sizing, operation and district heating network layout. Energy 2016;116:619–36. https://doi.org/10.1016/j.energy.2016.09.139.
[12] Wang H, Yin W, Abdollahi E, Lahdelma R, Jiao W. Modelling and optimization of CHP based district heating system with renewable energy production and energy storage. Applied Energy 2015;159:401–21. https://doi.org/10.1016/j.apenergy.2015.09.020.
[13] Oppelt T, Urbaneck T, Gross U, Platzer B. Dynamic thermo-hydraulic model of district cooling networks. Applied Thermal Engineering 2016;102:336–45. https://doi.org/10.1016/j.applthermaleng.2016.03.168.
[14] van der Heijde B, Fuchs M, Ribas Tugores C, Schweiger G, Sartor K, Basciotti D, et al. Dynamic equation-based thermo-hydraulic pipe model for district heating and cooling systems. Energy Conversion and Management 2017;151:158–69. https://doi.org/10.1016/j.enconman.2017.08.072.
[15] Franchini G, Brumana G, Perdichizzi A. Performance prediction of a solar district cooling system in Riyadh, Saudi Arabia – A case study. Energy Conversion and Management 2018;166:372–84. https://doi.org/10.1016/j.enconman.2018.04.048.
[16] Brumana G, Franchini G, Ghirardi E. Optimization and performance assessment of a solar district cooling system. AIP Conference Proceedings, vol. 2191, 2019. https://doi.org/10.1063/1.5138759.
[17] Remund J, Müller S, Kunz S, Schilter C. Meteonorm Handbook part II: Theory. 2012.
[18] McDowell TP, Bradley DE, Hiller M, Lam J, Merk J, Keilholz W. TRNSYS 18: The continued evolution of the software. Building Simulation Conference Proceedings 2017;4:2049–57. https://doi.org/10.26868/25222708.2017.516.
[19] Murray MC, Finlayson N, Kummert M, Macbeth J. Live energy trnsys -trnsys simulation within google sketchup. IBPSA 2009 - International Building Performance Simulation Association 2009 2009:1389–96.
[20] Franchini G, Brumana G, Perdichizzi A. Monitored performance of the first energy+ autonomous building in Dubai. Energy and Buildings 2019;205:109545. https://doi.org/10.1016/j.enbuild.2019.109545.
[21] ASHRAE. Fundamentals Handbook. S.I. Ameri. 1997.
[22] Lund R, Mohammadi S. Choice of insulation standard for pipe networks in 4th generation district heating systems. Applied Thermal Engineering 2016;98:256–64. https://doi.org/10.1016/j.applthermaleng.2015.12.015.
[23] Kristjansson H, Bøhm B. Advanced and traditional Pipe systems: Optimum Design of Distribution and service Pipes. 10th International Symposium District Heating and Cooling 2006:11.
[24] Brumana G, Franchini G, Ghirardi E, Perdichizzi A. Analysis of Solar District Cooling systems: The Effect of Heat Rejection. E3S Web of Conferences 2020;197. https://doi.org/10.1051/e3sconf/202019708018.

[25] Buffa S, Cozzini M, D'Antoni M, Baratieri M, Fedrizzi R. 5th generation district heating and cooling systems: A review of existing cases in Europe. Renewable and Sustainable Energy Reviews 2019;104:504–22. https://doi.org/10.1016/j.rser.2018.12.059.
[26] Eicker U, Pietruschka D, Haag M, Schmitt A. Energy and economic performance of solar cooling systems world wide. Energy Procedia 2014;57:2581–9. https://doi.org/10.1016/j.egypro.2014.10.269.
[27] Wetter M. GenOpt ® -- A Generic Optimization Program. Proc IBPSA's Building Simulation 2001 Conference, August 13-15, 2001 in Rio de Janeiro 2001:9.
[28] IRENA. Renewable Power Generation Costs in 2018. 2018.
[29] Fu R, Feldman D, Margolis R. U . S . Solar Photovoltaic System Cost Benchmark : Q1 2018. Nrel 2018:1–47. https://doi.org/10.7799/1325002.
[30] Davies G. the Potential and Costs of District Heating Networks 2009.
[31] Brumana G, Franchini G, Ghirardi E, Perdichizzi A. Techno-economic optimization of hybrid power generation systems: A renewables community case study. Energy 2022;246:123427. https://doi.org/10.1016/j.energy.2022.123427.