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Design and Performance Comparison of District Heating Systems in Milan and Riga

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***Abstract* – The work proposes a comparison between three heating configurations covering the demand of a new settlement: 1) centralized district heating system (DHC); 2) 5th generation district heating & cooling system (5GDHC) and 3) individual home heating and cooling (HHC) systems. Thermal and electrical loads are evaluated by transient simulations of a residential area with 80 buildings. The energy plants are based on different technologies: combined heat and power plants, gas-fired boilers, and domestic heat pumps. A transient numerical model has been developed for each solution. Every component is modelled according to performance maps provided by the manufacturers, allowing an accurate simulation in both design and off-design operating conditions. On an annual basis, the Latvian residential complex requires almost twice as much energy as the Milan one. The thermal losses in the district systems are 4.21 % in the Milan solution and 5.65 % in Riga. The district heating system coupled with a heat pump represents the best layout in terms of primary energy consumption in both locations, with energy savings of 50 % compared to other solutions. The use of 5GDHC is a good compromise that could increase the use of renewable energy. The adoption of a cogeneration plant is a good choice in the case of a centralized district system that allows the installation of high-efficiency genset. On the contrary, for small applications such as residential, the cogeneration results are expensive, and the conversion efficiency does not justify the installation.**

***Keywords* – Cogeneration; district heating; heat pump; 5th generation district heating system.**

1. INTRODUCTION

Worldwide, greenhouse gas emissions are affected by the increase of air conditioning systems [1]. Many studies focus on the development of new energy distribution systems with the aim of improving energy efficiency. New sustainable city design includes a district system as a viable solution to reduce environmental issues [2]. The fourth-generation centralized district system (DC) is the most common option [3]. However, in recent years, the emerging fifth-generation district heating and cooling (5GDHC) has proven to be the best solution for temperate climates due to its low-cost infrastructure, coupled with a high-efficiency reversible heat pump [4].

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To decrease reliance on fossil fuels, the implementation of renewable energy solutions compels the market to develop new and more effective methods for powering air conditioning systems with environmentally friendly energy. With detailed study and optimization [5], district systems and home solutions can be converted into fossil-free plants, ensuring a high level of reliability. The use of renewable energy sources emphasises the need for a system that performs well and has a good overlap between load and solar irradiance, particularly when cooling is required [6]. The combination of compression chiller with photovoltaic fields [7] is favoured by the market trend due to its easy integration into the existing grid infrastructure.

As part of the EU roadmap, the Italian government plans to increase the integration of renewable sources in the energy sector. To achieve this, storage systems are crucial in mitigating power fluctuations and ensuring a stable and reliable energy supply [8]. Furthermore, widespread implementation of electric energy storage systems, specifically lithium-ion batteries, is becoming increasingly significant in electric networks, despite not being economically feasible. The total cost is approximately 325 USD/kWh [9], with a cell cost of 176 USD/kWh [10].

The procedure for designing a district system requires a comprehensive evaluation [11] and detailed transient simulations, as reported by Wang [12] and Oppelt *et al.* [13]. Due to the large number of variables included in numerical models, optimisation techniques must be employed [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 for a new residential compound. The setup involves evaluating the heating and cooling load of the building under different climates condition (Italy and Latvia), as well as the operation and performance of the district system. The procedure is based on transient annual simulation and performs a detailed optimization to deliver the best techno-economic solution among three available technologies: 1) centralized district heating and cooling (DHC) system; 2) 5th-generation district heating and cooling (5GDHC) system; and 3) individual home central heating and cooling plants (HHC). To provide a complete assessment of 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 operation of the system includes three different energy sources: cogeneration, standard boiler and reversible heat pumps.

2. METHODS AND METHODOLOGY

The methodology section introduces and proposes the procedure adopted to assesses the layout evaluation and comparison. The modelling phase and has been based on the software Trnsys 18 [17] coupled with Trnsys3D plug-in [18]. The software Trnsys has been selected due to the modelling capability of dynamic simulation both for building and energy production and distribution. In the following sections, site meteorological data and hourly power demand profile are illustrated. The models of each technology are reported: main assumptions, technical data, performance outputs under design and off-design operation are presented for power generation and for storage systems.

Starting from the environment, a resume of ambient conditions of the selected location is reported in Fig. 1: profiles of temperature and radiation (Direct Normal Irradiance) are shown in Fig. 1 derive from the Meteonorm database [19]. The trend of the ambient temperature is linear, while the trend of the radiation shows the different distribution of cloudy days during the seasons.

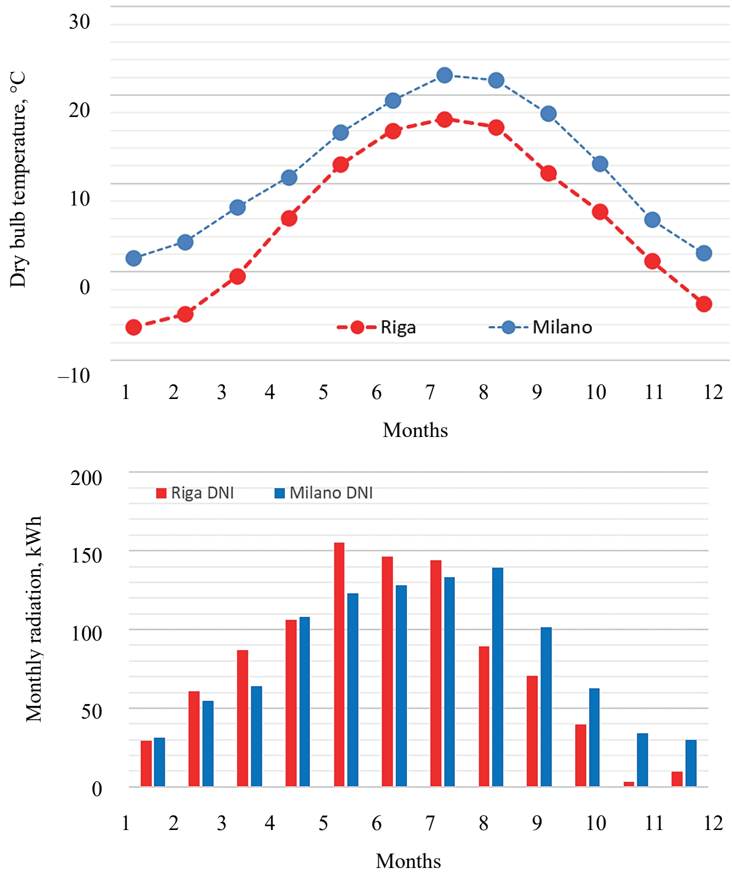

Fig. 1. Ambient conditions.

The load evaluation of a residential compound of 80 houses started from the real geometry of a two-floor 650 m^2 house and considering occupancy, lights, and appliances. Using software Trnsys a complete model of building and environment has been developed. The model of 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. The values highlight that the annual heating load is 35 % greater in Riga with respect to Milano but, more interesting is the monthly trend of heating load reported in Fig. 4. The trend indicates that the heating load is more aligned with the temperature distribution than with the radiation distribution.

Starting from the single building heating and cooling load, the model of district system coupled with the generation units has been developed. The building heating and cooling load has been considered as an input for the district system and the cumulative heating that include the thermal losses represents the input for the heating and cooling generation system. The three different distribution system has been described in the following paragraph whilst the generation system is reported in the paragraph heating and cooling sources.

TABLE 1. ANNUAL HEATING AND COOLING LOAD

Loads	Riga	Milano
Cooling load (sensible)	1247	8538
Cooling load (latent)	4224	11 801
Cooling load (total)	5470	20 339
Heating load (total)	115 473	68 551

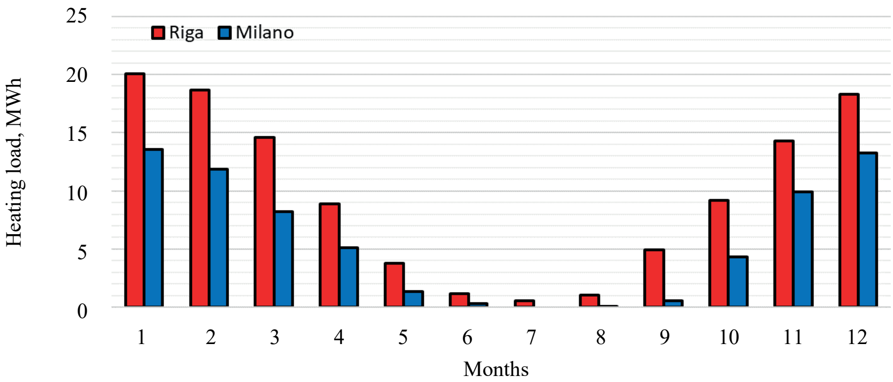

Fig. 2. Monthly heating load for the considered new settlement.

2.1. District Heating and Cooling (DHC)

The cooling load of the building was used as input for the district simulation. The simulation considered peak shaving effects and thermal dissipation in the network, as described in [15]. The piping design parameters, including insulation thickness of 5 cm and a design water speed of 2.75 m/s, were taken from technical literature [21], and suggested best practices [22], [23]. The district network layout specifies two pipes for cold distribution and two pipes for hot distribution. Heating and cooling are provided to the users by the heat transfer substation, which has a temperature difference of 7 °C.

2.2. 5th Generation District Heating and Cooling (5GDHC)

The 5th generation district heating and cooling technology is a highly advanced solution for building air conditioning. The system combines the reliability of the district system with the user-tailored solution of the home reversible heat pump. The selected layout is based on a two-ring solution with parallel flow. Temperature levels of 18 °C and 24 °C are recommended in the literature [24]. The temperatures of the ring fluctuate throughout the year in relation to the design levels and are stabilised using a centralised plant. Each building has a reversible heat pump installed and the off-design operation is simulated according to a performance map provided by the manufacturer.

2.3. Home Central Heating and Cooling (HHC)

In the domestic system, a central heating and cooling unit is used to meet the loads of the individual building. The heat pump operates in direct mode and its performance is based on a domestic heat pump (refer to the Table 3). For home applications, the standard solution is to use a dry cooler as a heat rejection system, which is the most commonly installed system in Europe.

2.4. District System Heating Load Evaluation

According to the proposed model, the heating load has been evaluated for the two selected locations and the three heating distribution systems. The results highlight the heat losses related to the traditional district system. On an annual basis, the Latvian residential complex requires almost twice as much energy as the Milano one. The thermal losses in the district systems are 4.21 % in Milano solution and 5.65 % in Riga, as seen in Tables 2 & 3. The heat losses related to the 5GDHC are not evaluated considering the low distribution temperature. Similarly, the domestic system has no distribution losses.

TABLE 2. OUTPUT NEW SETTLEMENT IN RIGA

		DHC	5GDHC	HHC
Peak Load	MW	3.58	3.387	3.408
Annual load	GWh	9.76	9.235	9.235
Annual losses	%	5.65	0.00	0.00

TABLE 3. OUTPUT NEW SETTLEMENT IN MILAN

		DHC	5GDHC	HHC
Peak Load	MW	2.23	2.14	2.17
Annual load	GWh	5.71	5.48	5.48
Annual losses	%	4.21	0.00	0.00

2.5. Heating and Cooling Sources

Moving to the energy system that provide heat energy to the district system, or to the building, the comparison has been made between three different systems.

The selected solutions are:

- Combined Heat and Power (CHP);
- Domestic or industrial Boiler (BL);
- Reversible Heat Pump (HP).

The components sizing has been based on the normalized peak power required by the district system or from the single user building. The combined heat and power are based on internal combustion engine driven by natural. The design output is considered different for large power plant and for domestic user according to different design efficiency as expected for different engine size [25], [26]. The performance evaluation under part-load condition is computed according to manufacturer specification. The main parameters of the CHP plants are reported on Table 4 both for the centralized system and the domestic one.

The boiler represents the most common solution for a heating plant. In the case of district system, the model considers an industrial grade 1 MW boiler with a rated efficiency equal to 0.95 while, for the domestic one the efficiency is considered equal to 0.87.

The heating load in home system is satisfied by a central system based on an air-cooled high efficiency reversible heat pump while, for the district systems (DHC and 5GDHC) the energy plants rely on a centralized industrial-grade reversible heat pump based on a seawater circuit in Riga and air as a heat source in Milano. The heat pump specification is reported in [27], Table 5 displays the main specifications of the system. The COP values, which refer to a 1 MW unit, remain constant at the nominal conditions regardless of the size of the unit. Conversely, off-design operation is calculated based on a performance map that takes into account temperature and part-load derating. As emphasised in the authors' previous work [28], the heat rejection system is a crucial aspect of the energy performance assessment. Here, the proposed solution is based on geothermal water with different seasonal variations and temperature levels for each of the sites.

TABLE 4. COGENERATION SYSTEM SPECIFICATION

		CHP for DHC	**CHP for 5GDHC**	**CHP for HHC**
	Unit	Value	Value	Value
Design electric output	kW	1000*	1000*	16*
Design thermal output	kW	1051	1051	42
Electric efficiency	–	0.39	0.39	0.23
Thermal efficiency	–	0.41	0.41	0.61

* The power rating is a typical value for the application

TABLE 5. HEAT PUMP SPECIFICATION

		HP for DHC	**HP for 5GDHC**	**HP for 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

3. RESULTS AND DISCUSSION

The result of the simulations highlights the large difference between the two locations, not only in terms of annual load, but also in terms of load distribution. The adoption of cogeneration plant is a good choice in case of centralized district system that allows the installation of high efficiency genset. On the contrary, for small applications, such as residential, the cogeneration results in expensive solution and the conversion efficiency does not justify the installation.

In the case of CHP systems, the electric and thermal power were provided by an internal combustion engine, as shown in Fig. 3, the domestic system appears to use less primary energy due to the lower efficiency of the small internal combustion engine, which provides a greater amount of heat energy. In the case of large CHP systems, the electricity production is comparable to the heat energy delivered with a ratio between electricity and heat produced close to 1.

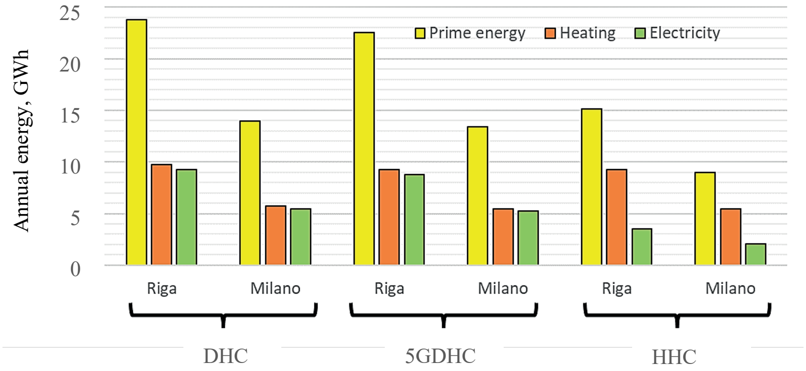

Fig. 3. Annual result for ICE cogeneration-based systems.

Fig. 4 reports the primary energy required by the boiler system, due to the heat loss in district system the 5GDHC requires less fuel to keep the system balanced. The home system, on the other hand, has no heat loss but lower boiler efficiency that need a greater amount of primary energy with respect to the other solution.

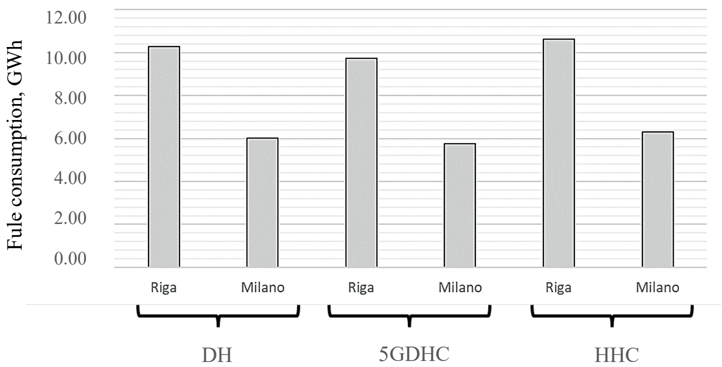

Fig. 4. Annual result for boiler-based systems.

Fig. 5 shows the annual average COP considered as energy consumption vs. energy production for the heating purpose. The figure points out that 5GDHC, compared with the centralized system, requires a bigger amount of electric energy due to the lower COP. The difference in COP is related to the size of the heat pump. Differently, between 5GDHC and home system, the size of the heat pump is the same but the connection to the district system provides a stable energy source that emphasizes the energy consumption.

Moving to the detailed analysis of system operation, as reported in Fig. 6 where a three-day operation is proposed for the two locations (left column Riga, right column Milano) for the CHP solution. The same result is proposed in Fig. 7 for the HP solution. The result highlights the bigger fluctuation in Milano due to the variation of ambient temperature with respect to Riga where the seawater provides a stable heat source for the systems. The home system heat pump in Riga shows a remarkable derating of the efficiency due to the low ambient temperature that suggest avoiding this kind of system in that region. Furthermore, due to the peak shaving effect the operation of district system appears smoothed with respect to the home system including a benefit in terms of system operation.

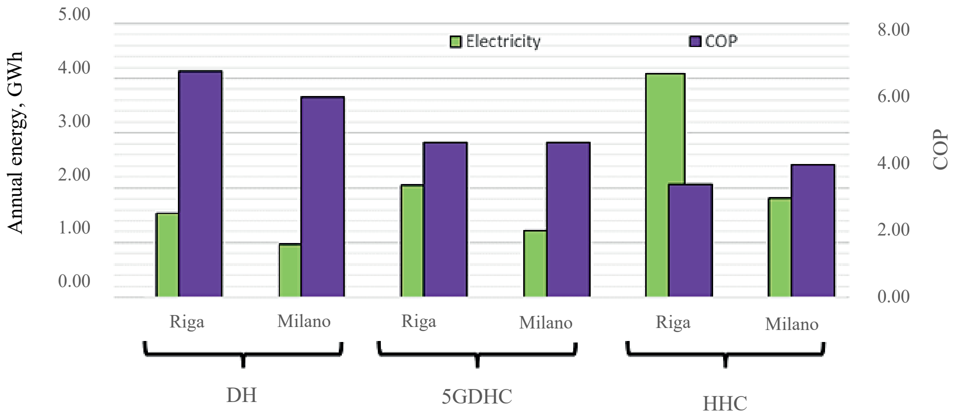

Fig. 5. Annual result for heat pump-based systems.

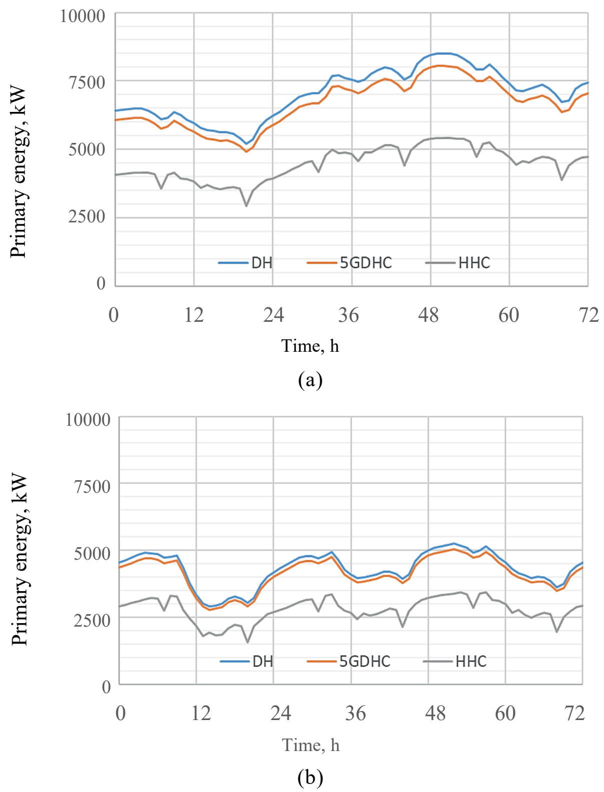

Fig. 6. Three-day systems operation for CHP system: a) Riga – CHP primary energy consumption (fuel heating value); b) Milano – CHP primary energy consumption (fuel heating value).

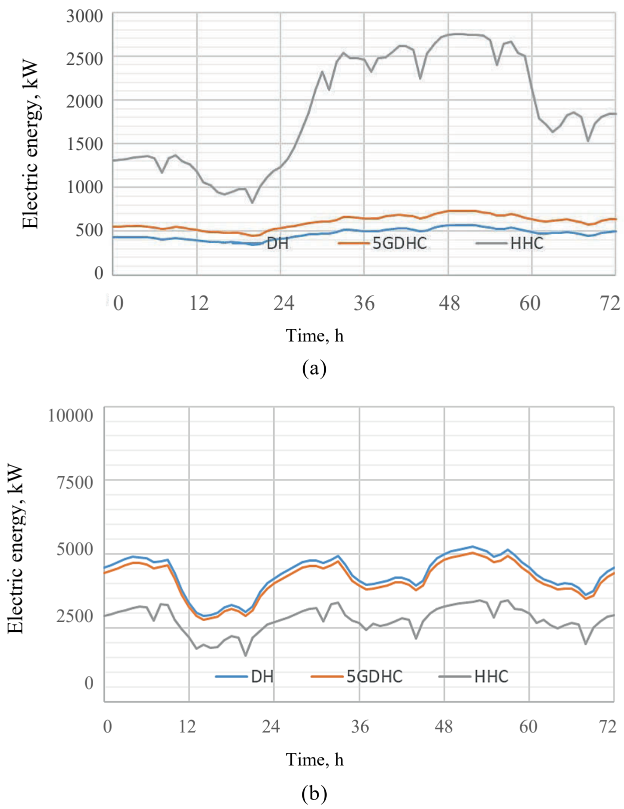

Fig. 7. Three-day systems operation for HP operation: a) Riga – HP energy consumption; b) Milano – HP energy consumption.

In order to propose a comparable result in terms of energy consumption, the electric consumption required from the heat pump solution has been converted in primary energy considering the national generation park efficiency and the amount of CO_2 emitted for each country.

In Italy 43.72 % of the annual electricity generation coming from renewable with respect to the 76.64 % achieved from Latvia [29]. Nevertheless, the amount of carbon dioxide emitted per unit of energy production, measured in kilograms of CO_2 per kilowatt-hour is equal to 0.2 in Italy and 0.17 in Latvia [30], due to the greater efficiency of the fossil generation mix in Italy.

The result, see Table 6, in term of primary energy consumption, highlights the low value of the heat pump consumption due to the high level of renewables included in the national energy mix. On the other side, the heat pump is the best solution for the centralized district system but the worst for cogeneration, this is due to the lower efficiency of small internal combustion engine that allow to produce a big amount of heating with respect to electricity.

The gas boiler represents a simple solution, cheaper with respect to the cogeneration but not considered for the new installation due to the complete dependencies from the fossil resources.

TABLE 6. PRIMARY ENERGY CONSUMPTION, MWH

	Riga			Milano		
	CHP	**Gas Boiler**	**HP**	**CHP**	**Gas Boiler**	**HP**
DH	23.79	10.27	1.41	13.93	6.01	1.05
5GDHC	22.52	9.72	1.88	13.37	5.77	1.31
HHC	15.14	10.61	3.60	8.98	6.30	1.96

4. ECONOMIC CONSIDERATION

The aim of the economic analysis is the evaluation of the system profitability considers the cost of all major components. The component sizing ensures the system operation, the district system budget evaluation takes into account the network infrastructure, branches, heat exchangers, and metering systems according to published data [31] and from the technical report [32].

The economic analysis does not include cost evaluation of a real business plan but considers costs that depend directly on the components size and plant layout. The

The evaluation of the Levelized Cost of Heating (*LCOH*) was calculated as listed in Eq. 1 according to a new approach as proposed in [33]. The *LCOH* considers the balance between import and export of electric energy with electricity cost equal to 0.05 USD/kWh for selling as reported in Table 7. The *CRF* represents the Capital Recovery Factor evaluated as listed in Eq. 2, where *Ny* represents the component lifespan (30 years for network systems, 25 years 5GDHC, and 25 years for Home System) and *i* represents the interest rate equal to 3 %.

$$LCOH\left(\text{EUR/kWh}\right)=\frac{CRF_i \cdot C_{\text{plant}}+O\,\&\,M}{Qheating} \tag{1}$$

$$CRF_i=\frac{i\left(1+i\right)^{Ny}}{\left(1+i\right)^{Ny}-1} \tag{2}$$

TABLE 7. BUDGET COSTS AND ECONOMIC SCENARIO

		DHC	**5GDHC**	**HHC**
	Unit	**Value**	**Value**	**Value**
Cost CHP system	EUR/kW	400	400	2000
Cost gas boiler	EUR/kW	12	12	100
Cost heat pump	EUR/kW	140	500	800
Cost network	EUR/N	7000	4000	0
Cost HX	EUR/N	3000	3000	0
Fuel cost	EUR/kWh	0.046	0.046	0.046
Electricity import	EUR/kWh	0.150	0.200	0.200
Electricity export	EUR/kWh	0.050	0.050	0.050

The results of the economic analysis are presented in Fig. 8. The figure illustrates that for a central district heating system, the adoption of an HP represents the optimal solution in terms of the levelized cost of heating energy, with an improvement in the result moving from cogeneration to the heat pump. In the case of 5GDHC, the optimal solution is ring stabilization with a gas boiler, although the results are comparable. In the case of a home system, the optimal system is a gas boiler in both locations. This is due to the limited installation cost, which affects the levelized cost of heating (LCOH).

In the case of a heating plant, across locations and network layouts, a combined heat and power (CHP) system maintains the LCOH at a constant level, with no significant variation. However, a gas boiler increases the heating cost only for a home system due to the greater installation cost (size effect). The LCOH trend for heat pump systems is observed to increase when moving from DH to home system. This is attributed to the rising installation cost and lower efficiency of domestic heat pumps.

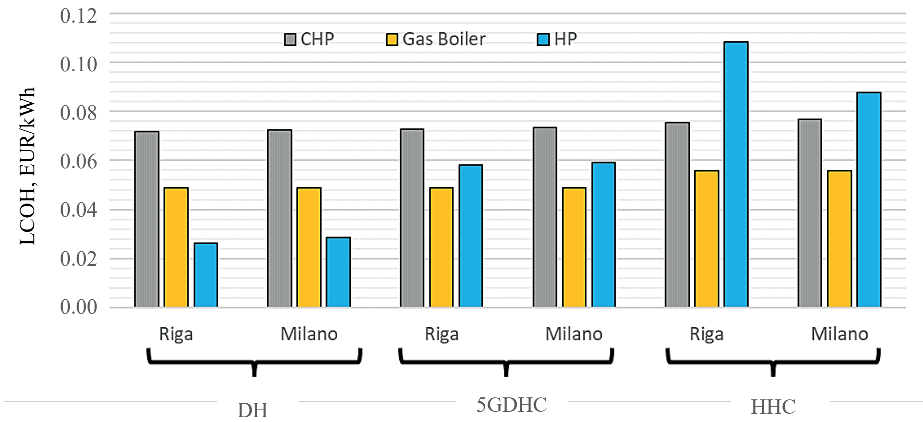

Fig. 8. Levelized cost of heating for the proposed layouts.

5. Conclusion

The paper deals with a comparison between two district heating layouts covering the demand of a new settlement: centralized district heating system, 5th generation district heating & cooling system compared with the individual home heating systems. Thermal and electrical loads are evaluated by transient simulations of a residential area with 80 buildings. The energy plants are based on different technologies: combined heat and power plants, gas-fired boilers and domestic heat pumps. A transient numerical model has been developed for each solution. Every component is modelled according to performance maps provided by the manufacturers.

On an annual basis, the Latvian residential complex requires almost twice as much energy as the Milan one. The thermal losses in the district systems are 4.2 % in Milan solution and 5.7 % in Riga.

The district heating system coupled with heat pump represents the best layout in terms of primary energy consumption in both locations, with energy savings of 50 % compared to other solutions. Nevertheless, the installation of home heat pump is affected by the fluctuation of ambient condition with a sensible efficiency derating in the Latvian region.

The use of 5CDHC is a good compromise that could increase the use of renewable energy and allows the felling of owned heating system.

Furthermore, considering the energy source, the adoption of cogeneration plant is a good choice in case of centralized district system that allows the installation of high efficiency genset. On the contrary, for small application as residential, the cogeneration results expensive and the conversion efficiency does not justify the installation.

REFERENCES

[1] Eveloy V., Ayou D. S. Sustainable district cooling systems: Status, challenges, and future opportunities, with emphasis on cooling-dominated regions. *Energies* 2019:12(2):235. 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(3):1381–1390. https://doi.org/10.1016/j.energy.2009.11.023
[3] Perez-Mora N. *et al*. Solar district heating and cooling: A review. *Int J Energy Research* 2018:42:1419–1441. https://doi.org/10.1002/er.3888
[4] Lund H. *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 Management* 2018:156:113–129. https://doi.org/10.1016/j.enconman.2017.10.078
[6] Inayat A., Raza M. District cooling system via renewable energy sources: A review. *Renew Sustain Energy Review* 2019:107:360–373. 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(3):37. 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* 2021:286:116533. https://doi.org/10.1016/j.apenergy.2021.116533
[9] Fu R., Remo T., Margolis R. U. S. Utility-Scale Photovoltaics- Plus-Energy Storage System Costs Benchmark. NREL 40. 2018.
[10] Goldie-Scot L. A Behind the Scenes Take on Lithium-ion Battery Prices. BloombergNEF, 2019. [Online]. [Accessed 12.05.2024]. Available: https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/
[11] Morvaj B., Evins R., Carmeliet J. Optimising urban energy systems: Simultaneous system sizing, operation and district heating network layout. *Energy* 2016:116:619–636. 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* 2015:159:401–421. 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 Therm Engineering* 2016:102:336–345. https://doi.org/10.1016/j.applthermaleng.2016.03.168
[14] Van der Heijde B. *et al*. Dynamic equation-based thermo-hydraulic pipe model for district heating and cooling systems. *Energy Conversion Management* 2017:151:158–169. 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 Management* 2018:166:372–384. 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 Conf. Proc*. 2019:2191. https://doi.org/10.1063/1.5138759
[17] McDowell T. P., Bradley D. E., Hiller M., Lam J., Merk J., Keilholz W. TRNSYS 18: The continued evolution of the software. *Build Simul Conf Proc* 2017:4:2049–2057. https://doi.org/10.26868/25222708.2017.516
[18] Murray M. C., Finlayson N., Kummert M., Macbeth J. Live energy trnsys simulation within google sketchup. *IBPSA 2009 – Int Build Perform Simul Assoc* 2009:1389–1396.
[19] Remund J., Mueller S., Kunz S., Schilter C. Meteonorm handbook, part II: theory. Bern, Switzerland, Meteotest, 2012.
[20] Franchini G., Brumana G., Perdichizzi A. Monitored performance of the first energy+ autonomous building in Dubai. *Energy Buildings* 2019:205:109545. https://doi.org/10.1016/j.enbuild.2019.109545
[21] ASHRAE handbook. Fundamentals (SI edition), (1997) Atlanta, Ga: American Society of Heating, Refrigerating, and Air-Conditioning Engineers 1985. 1997.
[22] Lund R., Mohammadi S. Choice of insulation standard for pipe networks in 4th generation district heating systems. *Applied Thermal Engineering* 2016:98:256–264. 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 Int Symp Dist Heat Cool, 2006. Technical University of Denmark, Lyngby.

[24] 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* 2019:104:504–522. https://doi.org/10.1016/j.rser.2018.12.059

[25] Pawlenka T. *et al*. Compact automatic controlled internal combustion engine cogeneration system based on natural gas with waste heat recovery from the combustion process. *Therm Sci Eng Prog* 2023:44:102042. https://doi.org/10.1016/j.tsep.2023.102042

[26] Rosato A., Sibilio S., Ciampi G. Energy, environmental and economic dynamic performance assessment of different micro-cogeneration systems in a residential application. *Applied Thermal Engineering* 2013:59(1-2):599–617. https://doi.org/10.1016/j.applthermaleng.2013.06.022

[27] Brumana G., Franchini G., Ghirardi E., Ravelli S. Optimization of Solar District Heating & Cooling Systems. *J Phys Conf Ser* 2022:2385:012113. https://doi.org/10.1088/1742-6596/2385/1/012113

[28] Brumana G., Franchini G., Ghirardi E., Perdichizzi A. Analysis of Solar District Cooling systems: The Effect of Heat Rejection. *E3S Web Conf* 2020:197. https://doi.org/10.1051/e3sconf/202019708018

[29] International Energy Agency (IEA). Energy Statistics Data Browser. [Online]. [12.05.2024]. Available: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=ITALY&fuel=Energy%20supply&indicator=TESbySource

[30] Our World in Data. Energy Country Profile 2024. https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table

[31] Brumana G., Franchini G., Ghirardi E. Potential of solar-driven cooling systems in UAE region. *Sol Energy Adv* 2022:2:100025. https://doi.org/10.1016/j.seja.2022.100025

[32] Davies G., Woods P. The potential and costs of district heating networks. A report to DECC, Pöyry Energy Consulting and Faber Maunsell AECOM, 2009.

[33] 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