A new approach for the hourly calculation of CO2 emission factors of the thermal energy production in District Heating Systems

A new approach for the hourly calculation of CO_2 emission factors of the thermal energy production in District Heating Systems

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Abstract:

Reducing the environmental impact of anthropic activities is critical and requires a proper analysis of CO_2 emissions. This study focuses on the thermal energy sector's emissions carbon footprint, which is essential for many public and private institutions. The current practice of using average national and annual emission factors (EFs) may lead to inaccurate results on specific local entities, particularly in the case of combined heat and power production. This study aims to refine the EF calculation considering a combined cycle cogeneration plant and an hourly time step for the analysis. The case study chosen is the district heating system (DHS) cogeneration plants of Turin, one of the largest DHSs in Europe. The defined thermal EF is applied to the user case study of Politecnico di Torino supplied by the DHS. The study focuses on the thermal energy needs of the university campus on an hourly and seasonal scale. The results reveal that the emission factor of a DHS calculated with this methodology is different from the one calculated with other methodologies or using national EFs, better representing the real situation. Since the load profile of a university facility represents tertiary sector energy activities, the methodology used in this study is easily replicable in different contexts. This study emphasizes the importance of accurately estimating CO_2 emissions, which is fundamental in reducing the anthropic environmental impact.

Keywords:

Emission factors, sustainable university, decarbonization, district heating system, combined cycle.

2. Introduction

Anthropic activities have a significant environmental impact and reducing carbon dioxide (CO_2) emissions is essential for mitigating climate change. In recent times, there has been an increasingly crucial need for institutions to address their emissions. In this regard, universities play a pivotal role, by reducing their carbon footprint they can contribute to their own sustainability and promote environmental awareness in other sectors. Quantifying carbon emissions is essential to measure progress towards decarbonization goals and one effective way to track progress is using ranking systems such as Green Metric [1]. Many non-governmental actors have joined the Race to Zero campaign, promoted by the United Nations, which encourages the achievement of decarbonization targets aiming to strive for carbon neutrality by the mid-century [2]. The energy sector is the most impactful sector in terms of carbon footprint and emissions [3]; in the European Union (EU), buildings are responsible for approximately 40% of total energy demand and produce 36% of greenhouse gas emissions [4]. Heating, ventilation, and air conditioning play an important role in overall energy demand in Europe, making it crucial to accurately measure and define their emissions [4]. The European heating and cooling sector are characterized by varying building types and relies primarily on decentralized production units within buildings. Natural gas is the predominant fuel, meeting 42% of the heating demand. Additionally, District Heating Systems (DHSs) supply 12% of the building sector's demand for space heating and domestic hot water [5]. Due to the strong electrification trend in the heating sector, recent studies have focused on a more accurate estimation of CO_2 emissions of electricity system. Specifically, emission factors (EFs) have been evaluated on an hourly basis, focusing on technologies such as heat pumps [6]. In parallel, similar studies have investigated the variability of EFs at the national level in electricity production. From this latter study, it appears that European Directives fix values of CO_2 EFs, neglecting their intrinsic temporal variability due to the mix of primary energy sources used in electricity generation hour by hour. The use of a fixed value for these parameters could lead to inaccurate or erroneous results in various processes [7]. Similar to electricity grids, DHSs are characterized by various types of centralized thermal power generation systems, resulting in comparable complexities in defining EFs as with electricity. However, there is a gap in the literature concerning the hourly variability of DHS emission factors.

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Additionally, current methodologies used to calculate emissions associated with DHSs do not take into consideration the high efficiency of technologies such as Combine Cycle Plants (CHP). Therefore, the goal of our study is to investigate the temporal variability of emissions produced by thermal energy consumption when a utility is supplied by CHP DHS. The new methodology presented is compered to different method currently in use. Specifically, we apply the methodologies presented to the case of the city of Turin's DHS, which is the most district-heated city in Italy and one of the main ones in Europe. The hourly EF developed with this methodology is then applied to the hourly thermal energy demand profile of the Politecnico di Torino providing an example of replicable application on tertiary sector users. As university facilities are representative of the energy consumption patterns of the tertiary sector, the methodology used in this study can be replicated in other contexts. By demonstrating how the environmental impact of energy consumption can be significantly affected by both the energy mix and the time of energy supply, we contribute to a better understanding of the challenges and opportunities for reducing carbon emissions associated with energy use in university facilities.

3. Methodology

3.1. Current methodologies for calculating CO_2 emissions for cogeneration plants

3.1.1. Allocation of CO_2 emissions in case of cogeneration heat and power combined cycle

Allocating CO_2 emissions in plants that generate both thermal and electrical energy is a complex issue. These plants produce heat as a by-product of electricity production, which adds complexity for a correct allocation of emissions. In Europe, DHS heavily rely on fossil fuel-based Combined Heat and Power plants (CHP), with cogeneration accounting for over 70% of the heat generated by EU member states [8]. Given the importance of cogeneration for district heating (DH), it is crucial to develop a methodology that can accurately account for the resulting CO_2 emissions.

Typically, DHS that supply large urban areas, are characterized by Combined Cycle CHP plants (CC). This type of plant combines two production phases, one based on gas and the other on steam. The high-temperature exhaust gases from the Gas Turbine (GT) are used to produce steam in a Heat Recovery Steam Generator (HRSG), which is then fed into a Steam Turbine (ST) to generate additional electrical power. CCs are typically used both in industrial settings that require the production of steam, superheated or hot water, and for DHS. They come in various sizes, ranging from 50 to 400 MWe, and offer electric efficiencies of approximately 45-58%. DHSs, which utilize combined cycle power plants, typically generate 80-90% of their annual heat energy production through cogeneration [9]. These plants produce thermal energy throughout the heating season but require additional support from backup generators during the coldest months and during peak demand hours. Thermal storage systems, which use hot water tanks to store excess heat generated during low-demand periods, are typically utilized in DH networks to manage the demand and supply of heat efficiently. During peak hours, the stored heat is released to ensure a consistent flow of heat to customers. Furthermore, these thermal storage systems can be charged using renewable sources if available, or by cogeneration plants. This approach not only reduces energy waste and improves the overall efficiency of the system, but also promotes the utilization of renewable energy sources in DH networks.

A simplified diagram illustrating the relationship between fuel input and the resulting output of electricity and heat for a typical DHS with a CC unit is shown in Figure 1. The nomenclature used in the figure is used in the following sections to explain the various methodologies available in the literature for calculating the DHS emission factor. The energy balance shown in the figure is annual.

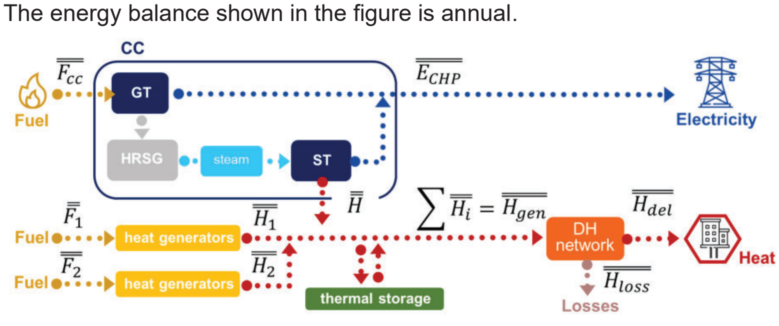

Figure 1. District heating system, CHP general scheme and relative nomenclature

3.1.2. Eurostat, Ispra and IPCC methodology (Method E)

The IPCC's Working Group 3, in Annex 2 Metrics and Methodology [10], defines carbon dioxide emission factors for electricity and heat based on the ratio between CO_2 emissions due to fuel inputs of power plants

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and the delivered electricity and heat. The CO_2 emission factors of each fuel type, as defined in IPCC (2006) [11], are multiplied by the fuel inputs. The calculation of CO_2 emission factors for electricity and heat is conducted at the country level. Also the 2020 annual report on emission factors drafted by Ispra[1] and Snpa[2] [12] and Eurostat 2016 annual questionnaire report [13] present the same methodology for allocating the fuel between the electricity and heat generation components.

This methodology can be expressed in the following way:

$$\overline{f_{DHS,HE}} = \frac{\overline{\overline{F_i}}}{\overline{\overline{H_{del}}} + \overline{\overline{E_{CHP}}}} * f_{i,F} \qquad \left[\frac{kg_{CO_2}}{kWh}\right] \qquad (1)$$

According to the 2020 Ispra annual report, this formula is recommended only when national administrations have not adopted a more precise methodology for reporting combined heat and power (CHP) on a unit basis. Using this methodology, that we will call method E, the resulting EF is 0.30 kg_{CO2}/kWh.

3.1.3. UNI EN 15316-4-5:2018 methodology (Method U)

A different methodology for multi-output DHS is detailed in the regulatory document UNI EN 15316-4-5:2018. This approach has been utilized in various publications [14] and has been adopted as a standard methodology for creating CO_2 emission inventories for Italian universities, members of the Italian sustainable development network (RUS[3]). The formula for this methodology is the following:

$$\overline{f_{DHS,H_{del}}} = \frac{(\sum_i \overline{\overline{F_i}} f_{i,F} - \overline{\overline{E_{CHP}}} f_{el})}{\overline{\overline{H_{del}}}} \qquad \left[\frac{kg_{CO_2}}{kWh}\right] \qquad (2)$$

The issue with this approach arises in situations where the production of electrical energy from cogeneration systems is very high, resulting in a negative value of the derived emission factor. In case of negative values, the regulatory document recommends considering these cases as zero-emitting, underestimating the actual emissions from thermal energy consumption.

3.2. Introducing a new methodology for determining emission factors

The emission factors determined by current methodologies don't reflect the actual value that should be utilized in a real DHS supplied by CC CHP. Hence, it is necessary to develop a different approach that combines both hourly and simplified annual analyses for calculating CO_2 emissions in DHS.

3.2.1. Combined cycle cogeneration heat and power plants for district heating systems

As explained in section 3.1.1, in CC systems it is possible to recover heat for industrial purposes or DHS use from the steam cycle. Steam can be supplied by extracting pass-out steam at an intermediate point in the turbine. The rest of the steam continues to the exhaust, thereby generating further power, and exits the process at a lower pressure. Therefore, whenever there is a thermal demand and the plant operates in cogeneration mode, steam extraction results in less electricity production. A typical operating diagram for each plant is shown in Figure 2.

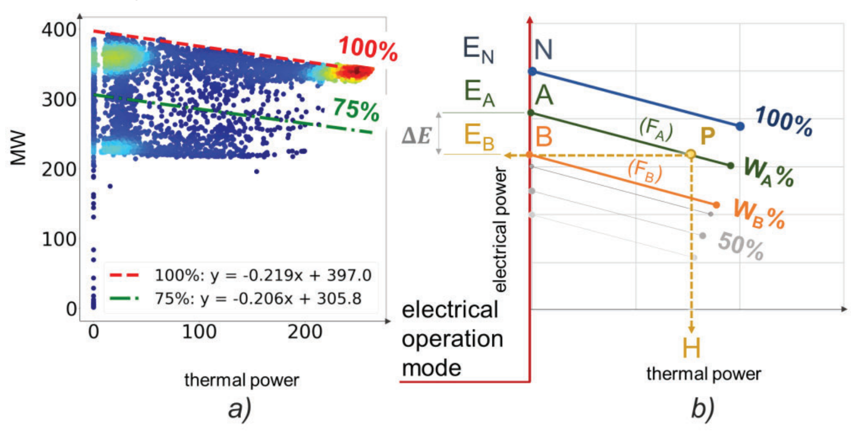

Figure 2. CHP operating diagram partial load. a) real operating diagram: hourly energy production (equation of regression lines *[15, 16]*); b) working point P

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[1] Istituto Superiore per la Protezione e la Ricerca Ambientale.
[2] Sistema Nazionale per la Protezione dell'Ambiente.
[3] Rete delle Università per lo Sviluppo Sostenibile.

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The y-axis shows the electrical power generated at various nominal loads, while the x-axis represents the corresponding heat output. The point N represents the working condition at nominal load in *electrical operation mode*. Thermal power is not generated, and electrical power corresponds to the nominal value. By working on the 100% load operating characteristic, the heat output increases, and the *cogeneration condition* is reached. Each load has a characteristic regression line whose points are characterized by the same fuel inlet power (F). Figure 2a shows the real hourly operation in one year of operation of a CC. A generic working point P in cogeneration condition at load W_A% is considered. The point is characterized by a thermal power H and an electrical power E_B. At the same fuel input power F_A and considering the electrical operation mode, a higher electrical power equal to E_A would be obtained. The production of thermal energy causes a reduction in the amount of electricity produced.

$$\Delta E = \mathrm{E}_A - \mathrm{E}_B \qquad [MW] \qquad (3)$$

The ratio of the two output energies K is the *cogeneration gain*, expressed in the equation (2). K is inversely proportional to the slope of the loads regression lines and it is approximately constant as leads changes. ΔE can consequently be expressed as in equation (5).

$$K = \frac{H}{\Delta E} = cost \qquad [MW] \qquad (4)$$

$$\Delta E = \frac{H}{K} \qquad [MW] \qquad (5)$$

By analyzing the hourly operating experimental data of a few combined-cycle plants, it was possible to outline a general trend in energy performance in *electric operation mode*. Isolating the hourly data in which the CC operated in electrical mode and excluding the transient operating values, the real operating data were averaged to obtain the percentage trend shown in Figure 3.

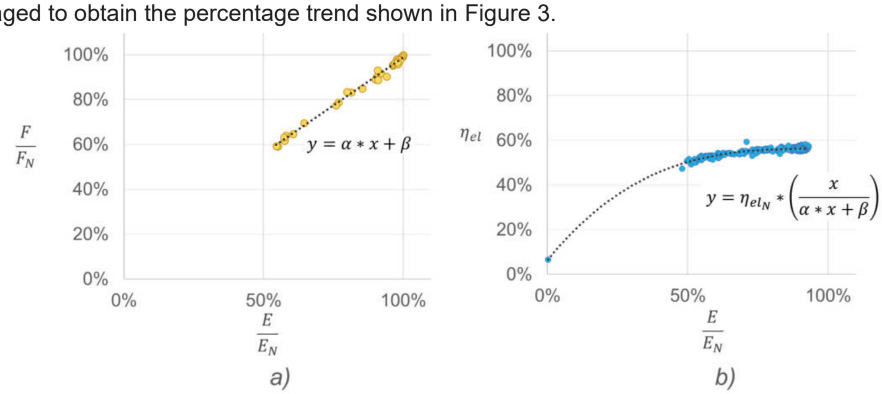

Figure 3. Electrical operation mode working performances of a generic CC unit. a) fuel inlet power; b) CC electrical efficiency.

Figure 3a shows the linear dependence of the fuel inlet power with respect to the load of the generated electrical power (equation (6)). The characteristic equation of CC electrical efficiency with respect to the electrical load variation is obtained. As shown in figure (b) the points of real operation validate the trend.

$$\frac{F}{F_N} = \alpha \frac{E}{E_N} + \beta \qquad [MW] \qquad (6)$$

3.2.2. Combined Cycle emission factor

To determine the *hourly emission factor* of a generic CC supplying a DHS, we consider a generic operating point *P* (Figure *2*b). As explained in the previous section, the generation of thermal energy results in a lower amount of electrical power generated ΔE for the same amount of fuel used. It is possible to allocate ΔE with the additional fuel inlet power ΔF consumed in cogeneration condition. The same electric power E_B could in fact be obtained by working at a lower load W_B% with less fuel input power F_B. From equation (6)(6)**Errore. L'origine riferimento non è stata trovata.** F_A and F_B are defined:

$$F_P = F_A = F_N \left(\frac{\alpha E_A}{E_N} + \beta\right) \qquad [MW]$$

$$F_B = F_N \left(\frac{\alpha E_B}{E_N} + \beta\right) \qquad [MW]$$

The nominal condition N in electrical operation mode at 100% load is characterized by electrical efficiency:

$$\eta_{el,N} = E_N / F_N$$

Therefore ΔF is defined:

$$\Delta F = F_A - F_B = \alpha \frac{\Delta E}{E_N} * F_N = \frac{\alpha}{K} \frac{H}{\eta_{el,N}} \qquad [MW] \qquad (7)$$

The additional amount of inlet power required must be multiplied by the fuel EF and normalized to the heat output:

$$f_{CC,H} = \frac{\Delta \mathrm{F} * f_{NG}}{\mathrm{H}} = \frac{\alpha}{\mathrm{K}} * \frac{1}{\eta_{el,N}} * f_{NG} \qquad \left[\frac{kg_{CO_2}}{kWh}\right] \qquad (8)$$

The remaining amount of fuel inlet power F_B is attributed to CO_2 emission on hourly electrical energy generated. It would, in fact, have been equally produced in the case of electric power generation in the electrical operation mode. In this case in contrast to the thermal EF, the hourly electric emission factor is not constant. It varies following the same trend as the electrical efficiency shown in Figure 3b.

3.2.3. District heating system emission factor

DHSs have different layout configurations based on the served volumetrics and climatic zone. These configurations can vary based on the type of generator employed, the characteristic size of each generator, and the number of generators installed. The various generation groups produce thermal energy with different strategies based on thermal demand and economic and environmental dispatching considerations. Therefore, the CO_2 emissions associated with the use of heat from a DHS depend not only on the type of generators involved in the annual production but also on the way they produce thermal energy hourly and during different seasons. To correctly assess the DHS thermal EF, it is, therefore, necessary to define the amount of thermal energy produced for each generation unit hour by hour. The DHS thermal emission factor is the weighted average of each characteristic EF of the fuel and generator used multiplied by the thermal energy delivered. To express the emission factor $f_{i,H}$ with respect to the energy produced by the generator instead of that of the input fuel F_i as used in methods E and U, we define the relationship between the characteristic EF of the fuel and the efficiency of the generator.

$$f_{i,H} = \frac{f_{i,F}}{\eta_i} \qquad \left[\frac{kg_{CO_2}}{kWh}\right] \qquad (9)$$

For DHS in which a part of thermal energy is generated by a natural gas CC unit in combination with other types of heat generators, CC thermal emission factor is defined in equation (8). The energy delivered by the storage system is associated with the EF of the generator that predominantly charges the storage. Methods E and U calculate the DHS emission factor with respect to the energy supplied to the users H_{del}. Therefore, the heat loss factor $p\%$ on the distribution network is defined:

$$p\% = 1 - \frac{H_{del}}{H} \qquad [\%]$$

The DHS emission factor expressed as the ratio between the tonnes emitted and the energy delivered to the user can be defined as:

$$f_{DHS,H_{del}} = \frac{H * f_{CC,H} + \sum H_i * f_{i,H}}{H_{del}} = \frac{H * f_{CC,H} + \sum H_i * f_{i,H}}{H_{gen}(1-p\%)} = f_{DHS,H_{gen}} * \frac{1}{1-p\%} \qquad \left[\frac{kg_{CO_2}}{kWh}\right] \qquad (10)$$

The definition of heat delivered to the user excluding network losses requires specific discussion. Network losses are typically defined as a percentage of the total energy delivered annually. The incidence of losses on an hourly basis cannot be considered constant. In the summer period when the thermal demand is low, the energy that is produced is mainly dispersed to keep the entire network at temperature. Therefore, network losses are very significant, and the EF reaches values much greater than 1.

The emission factor can be expressed as the sum of the emission factor of losses and the emission factor of thermal energy consumptions.

$$f_{DHS,H_{del}} = f_{DHS,H_{gen}} * \frac{p\%}{1-p\%} + f_{DHS,H_{gen}} = f_{DHS,losses} + f_{DHS,cons} \qquad [kg_{CO_2} kWh] \qquad (11)$$

3.2.4. SEA Method

The application of hourly emission factor outlined in equation (11), can be difficult for a typical user connected to the DHS. In fact, the method assumes knowledge of DHS's hourly generators production, DHS hourly network losses, and hourly heat demand profile. The hourly load profile of the building may be known or calculable from consumption data with daily or monthly steps. On the other hand, system operating data

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may not be public and available. A *simplified method* (SEA[4] method) for calculating emissions is therefore proposed. Equation (12) can be adopted by replacing the hourly energy with the energy delivered annually by each heat generator. The first term of the emission factor relating to network losses is an annual average value. For this reason, in the case of users characterized by winter heat load profile, the value of emitted tons of CO_2 may not be representative. Therefore, it is appropriate to simplify the expression (equation (13)).

$$\overline{f_{DHS,H_{del}}} = \frac{\overline{\overline{H}} * f_{CC,H} + \sum \overline{\overline{H_i}} * f_{i,H}}{\overline{\overline{H_{gen}}}(1-\overline{\overline{p\%}})} = \overline{f_{DHS,H_{gen}}} * \frac{\overline{\overline{p\%}}}{1-\overline{\overline{p\%}}} + \overline{f_{DHS,H_{gen}}} \qquad \left[\frac{kg_{CO_2}}{kWh}\right] \qquad (12)$$

$$\overline{f_{DHS,H_{del}}} = \overline{f_{DHS,H_{gen}}} * \left(\frac{1}{1-\overline{\overline{p\%}}}\right) \qquad \left[\frac{kg_{CO_2}}{kWh}\right] \qquad (13)$$

3.3. Thermal energy demand profile evaluation

To calculate the hourly CO_2 emissions resulting from the Thermal Energy Consumption (TEC) of a tertiary user connected to a DHS, the first step is to gather data on the actual hourly energy consumption of the buildings. If energy demand profile is not available, it is still possible to estimate the energy consumption using specific values that consider external average temperature. A replicable methodology for the creation of a profile for other buildings with a similar occupancy profile is proposed.

3.3.1. Daily thermal energy consumption patterns and relation with external temperature

To investigate the thermal energy demand profile, the first step is to select the buildings to be included in the analysis and gather relevant energy-related data, such as energy consumption, variation in heated volumes, and average external temperature. By obtaining hourly data, it becomes possible to observe variations in consumption over time of day, external temperature, and day of the week. To facilitate year-to-year comparisons, we used the academic year (e.g., October to September) rather than the solar year. This enables the analysis of consumption trends during the same heating season, thereby minimizing potential errors arising from changes in heated volume across different years.

In the present case study, hourly data were collected from October 2021 to September 2022 for the demand side (University energy consumption), and from October 2010 to September 2011 for the production side (DHS data). Hourly consumption data of the university user are recorded in the heat exchange substation of the DHS serving the city and the analyzed user. In recent years, obtaining hourly energy consumption data from buildings has become increasingly accessible, although it is more challenging to obtain such data for the 2010-2011 heating season. With the improvement of data analysis services, it will be easier to perform hourly considerations in the future. In this case, however, we were forced to use the 2010-2011 period as a reference and consequently recalculate the hourly consumption. To do this, we used Energy Signature (ES) and load profile variation. As the variation in heated volumes between these two periods was negligible, this parameter was considered constant.

The analysis has allowed the identification of similar consumption pattern for the working midweek days: Tuesday, Wednesday, and Thursday. Monday consumption is higher due to its early heating starting time, Friday and Saturday have a lower thermal consumption because of a lower occupancy ratio. The midweek days were therefore used as Reference Days (RD) to create a daily ES that more accurately represents the buildings' behaviour of these days.

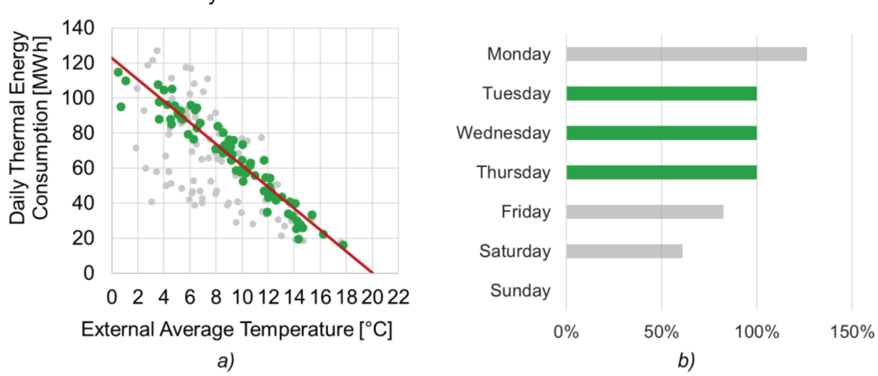

Figure 4. a) Daily Energy Signature, relationship between thermal energy consumption and external average temperature b) Ratio between TEC of a specific day of the week and average TEC of RD

[4] Sistemi per l'Energia e l'Ambiente.

To create a more representative linear regression model from the ES, some data was excluded: National holidays; days right after a day of building closure; and Mondays, Fridays, Saturdays, and Sundays. Daily average external temperature of 2010-2011 was then used in the equation of the ES trend-line. This output enabled the estimation of the daily TEC for all days with behaviour similar to RD.

To allocate the correct daily TEC for each day of the week, the ratio between the TEC of other days in the week and the average TEC of the RD was calculated for each week of the heating season. By taking the trimmed mean of these ratios, more realistic percentages were obtained as shown in Figure 1.b. The following specific considerations were made for the specific case study.

- On Monday, energy consumption is higher than the RD (126%) due to an early start time for heating after Sunday closure.
- On Friday, the occupancy rate of the facility decreases in the late afternoon and shutdown hour is later, leading to lower consumption than the RD (83%).
- On Saturday, the facility is only open in the morning, and its energy consumption is lower (61%).
- On Sunday, the facility is closed, with zero energy consumption.

To obtain the actual daily consumption, the values obtained from the linear regression model were multiplied by the ratios shown in Figure 4.b depending on the actual days of the week in 2010.

$$H_{s_{daily}} = \sum_{0}^{23} H_{hh} \qquad [kWh] \qquad (14)$$

This methodology enabled the calculation of daily heat consumption, denoted as $H_{s_{daily}}$, for the heating season 2010-2011. With these daily data, an hourly consumption profile was created using the methodology described in the following chapter.

3.3.2. A replicable methodology for identifying typical hourly heat demand profiles

A Python-based calculation method was created and developed to define the hourly TEC of a typical user. The model was built using daily energy consumption data obtained as explained in the previous chapter. The aim was to create hourly profiles depending on the days of the week and the months of the year. To express the hourly load, the ratio of hourly consumption to the total daily TEC was calculated (15).

$$L_{hh} = \frac{H_{\mathrm{hh}}}{\sum_{0}^{23} H_{hh}} \qquad [-] \qquad (15)$$

The hourly load was averaged for each month and day of the week. Afterwards, a matrix was extracted that contained the hourly percentage heat load values characteristic of the day of the week and month.

The Python model requires as input the daily energy consumption data, which can be obtained from the provider or using the energy signature and daily average external temperature of the same period for which CO_2 emissions are being calculated. Based on the required year, a usage schedule is developed, which can be modified in case of scheduled closures on non-holiday days.

The energy consumption value is then distributed over hourly values based on the percentage hourly load characteristic of the month and day being analyzed, resulting in the user's daily hourly consumption for the entire thermal season. By utilizing this calculation method, a typical hourly load profile can be obtained, which can be replicated for tertiary utilities that have similar heat management systems.

4. Results

4.1. Case study description

4.1.1. Thermal energy profile in the main campus buildings of Politecnico di Torino

The case study selected to develop and apply the new methodology of CO_2 emissions calculation from a user perspective is the Politecnico di Torino. Specifically, the analysis focuses on the hourly thermal energy consumption of the university's most energy-intensive DH substation. The reference period chosen is the academic year 2010-2011 as hourly data from DHS side was available for that period. Since hourly data of DHS substation was available from 2021 to 2023, the methodology described in section 2.3 was applied using data from October 2021 to September 2022. To ensure a representative heating season, data from the period of extended Covid-19 restrictions was excluded.

By applying the previously described methodology, a typical thermal consumption profile was generated for the reference heating season and hourly TEC data was extracted. The annual consumption of the reference buildings was 11.1 GWh. The aim of the chapter 3.2 is to calculate the resulting CO_2 emission using both hourly and yearly calculation.

The analysis enabled to show that start-up and shut-down times vary based on the month and outdoor temperatures, as well as the day of the week. An earlier start-up time of approximately one hour is observed on Mondays to warm up structures that have cooled down during Sunday, resulting in higher total energy consumption than on other days. Conversely, Friday sees an earlier shut-down time than other days by

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approximately one hour. Heating on Saturdays ceases around 1 pm, and no heating is required on Sundays due to the facility being closed.

4.1.2. Turin district heating system

Knowing the hourly thermal load profile of the consumer, to define CO_2 emissions, it is necessary to define what is happening at the energy generation level. Therefore, the DHS in Turin is analyzed from the energy point of view. The data used in this study are divided into two sets. The first set includes information on the production of electric and thermal energy, natural gas consumption, water temperature, and water flow rate inputs into the distribution network for all the generation groups of the Torino DHS from 2001 to 2011. The second set of data covers the period from 2010 to 2015 and is focused exclusively on the combined cycle power plants. Data cover hourly thermal and electric energy production, natural gas consumption, and carbon dioxide and pollutant emissions. The EF is being calculated for the 2010-2011 heating season because data are complete and comparable from both datasets. The DHS is supplied by three plants located in three different areas of the city. In the main plant, two combined cycles (CCs) and three Integration and Backup Boilers (IBBs) are installed. The other two plants consist of IBBs and a storage system (STO). The installed capacities are summarised in Table 1.

Table 1. Turin DHS thermal power installed (2010-2011)

type of generator	number, -	thermal power, MW	electrical power, MW	storage capacity, m^3
CC	2	520	760	-
IBB	9	651	-	-
STO	1	-	-	2’500

To analyse the operation of the two combined cycles, thermal power and electrical power are represented as a set of two-dimensional coordinates x and y (Figure 5). The CC energy output for each hour of operation is represented by a point. Using the *gaussian_kde* class of the *scipy.stats* module in Python, it is possible to estimate the probability density of the two-dimensional data represented by x and y. The mathematical model used by the KDE is based on the convolution of a core function with the input data. In this case, the KDE uses a Gaussian kernel to evaluate the probability density of the data, producing a continuous function that describes the probability distribution of the two-dimensional data. For both CCs (Figure 5 a and b), the point density is highest in the operation region of in cogeneration condition at full load. This is followed in order of frequency by the region in electrical operation mode typical in summer period when users’ thermal demand is lowest. A threshold operating zone of 230 MWe can be identified from the graph for both combined cycles. The output points are positioned along the regression lines representing operation from electrical to cogeneration operation at variable loads. As described in section 3.2.1, the slope of regression lines at variable loads are considered approximately constant. A change in slope is not significant to the emissions factor calculation. The slope is inversely proportional to K (equation (4)) and in Figure 5 a and b are equal to 4.5 and 4.3 respectively.

To simplify the simulation of plant operation, the outputs of the two CCs have been summed up (Figure 5c). The average cogeneration gain K_{ave} has been calculated and is equal to 4.4. In Figure 5c, the point density is higher when only one CC operates in electrical mode (summer periods) and when both CCs operate in full cogeneration condition (winter periods).

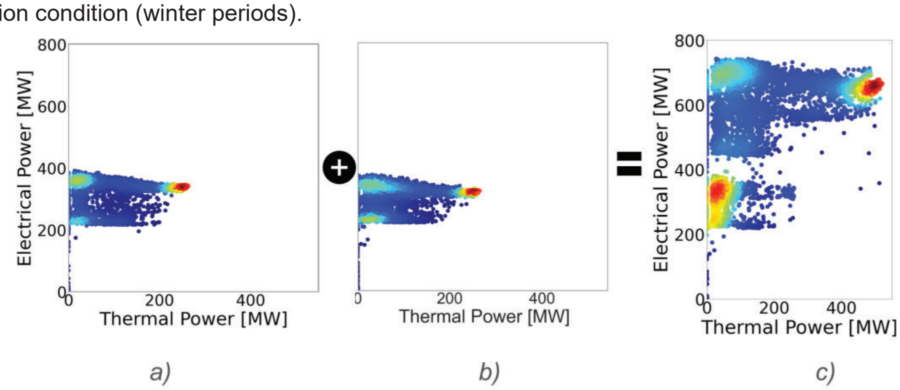

Figure 5. CC hourly energy output. a) CC_1; b) CC_2; c) $CC_1 + CC_2$

CCs produce 85% of the annual thermal energy, the remaining amount is produced by IBBs 13% and STO 2%.

4.2. CO_2 emissions in universities

4.2.1. Turin district heating emission factor

Starting from the overall operating data of the two CCs, the regression line shown in Figure 3a is derived. The characteristic coefficient α of the combined cycle is 0.902. The EF of the combined cycle (equation (8)) is 0.074 kg_{CO_2}/kWh. As shown in Table 1, the Turin DHS is connected with thermal storages. An analysis of the operation of the generation components hour by hour shows that the charging of the storage tanks occurs during night periods and during daytime periods when the thermal demand is lower. During such periods, the only operating generators are the CC units. For this reason, the storage unit also has an EF of 0.074 kg_{CO_2}/kWh.

By analysing the hourly operation of the heat generators of the DHS in Turin and applying equation (9), the hourly emission factor $f_{DHS,cons}$ is obtained. Figure 6a shows the hour-by-hour emission factors for the months of December, January, and February. Three different trends are identified. The points with a constant EF of 0.074 kgCO2/kWh are associated to *operating configuration 1*. It corresponds to the hours in which the thermal energy is exclusively produced by CCs and CCs with STO. As the thermal demand increases, the heat production is integrated by IBBs. The EF increases as the contribution of IBBs becomes more and more relevant. Thermal energy production from CCs, STO, and IBBs is represented by *operating configuration 2*. The 2010-2011 winter season was characterized by a few operation hours in which the thermal demand was satisfied by a single combined cycle CC at which the heat produced from IBBs was integrated. This operating configuration is represented by the *operating configuration 3*. The EF reaches the highest values. The average hourly emission factor $f_{DHS,cons}$ for each month is represented in the graph in Figure 6b.

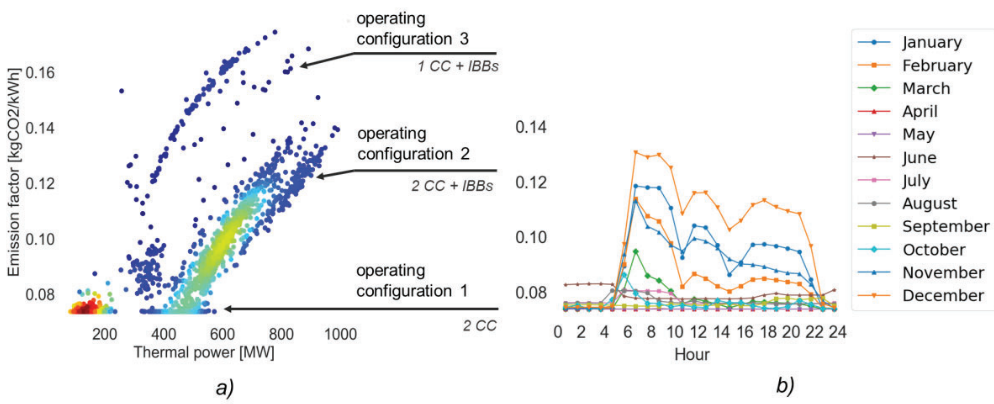

Figure 6. hourly EF (consumption factor). a) EF with respect to thermal energy generated in winter period; b) average EF with respect to time of day in the different months of the year

While in the summer months the emission factor $f_{DHS,cons}$ is lower, this is not true for the emission term related to network losses $f_{DHS,losses}$. Network losses contribution is lowest in the daytime hours of the heating season; it is most relevant in the night-time period, and it is highest in the summer period when the energy delivered is minimal and equal only to that required for domestic hot water production.

4.2.2. Annual emission factors methodologies comparison

To define the annual EF of the Turin DHS in the 2010-2011 thermal season, the annual energy performance is calculated. The total energy produced is 1'760 GWh_t, of which 8% is loss to the distribution network.

Table 2 shows the annual thermal emission factors calculated using the three methodologies presented in the previous sections. *SEA method* allocates the emission factor into two contributions: one related to heat losses in the distribution network, and the other related to actual thermal energy consumption. The EF obtained using this method is significantly lower than those obtained using the other two methods. *Method E* outputs an emission factor that is approximately three times higher than the one obtained using the SEA method proposed, and even higher than the EF of natural gas (0.202 kg_{CO_2}/kWh [17]). This implies that users who satisfy their thermal energy needs using DHS emit more tons of CO_2 than those who use a single natural gas boiler considering the same thermal energy consumption. Finally, *method U* considers electrical energy generated in cogeneration and produced as a substitute for fossil-fuelled non-cogeneration national thermoelectric plants. The electrical emission factor applied is the Italian gross thermoelectric production (fossil fuels only) as of the year 2010 and is equal to 0.565 kg_{CO_2}/kWh [12]. Method U generates a negative DHS thermal emission factor. The EF must be replaced by zero value. This implies that the production of thermal energy from DHS results in an inappropriate cutback of CO_2.

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Table 2. annual emission factor comparison

		Losses factor, kg_{CO_2}/kWh	Consumption factor, kg_{CO_2}/kWh	*Total factor* , kg_{CO_2}/kWh
Method E	(eq. (1))	–	–	0.302
Method U	(eq.(2))	–	–	– 0.421 (0)
SEA method	*(eq.* (11))	0.009	0.093	0.102

4.2.3. Application of methodologies to case study and corresponding CO_2 emissions

The emission factors calculated (Table 2) are applied to the consumption of the 2010-2011 heating season of Politecnico di Torino. In the 2010-2011 heating season, the annual thermal energy consumption calculated for the user case study is 11.1 GWh_t.

Table 3. Politecnico di Torino CO2 emission. 2010-2011 heating season

	Thermal losses, CO_2 t	Thermal consumption, CO_2 t	**Total, CO_2 t**
Method E	–	–	**3'350**
Method U	–	–	**0**
SEA Method	96	1'035	**1'131**
Hourly approach	42	1'087	**1'129**

Annual CO_2 emission values are compared with the hourly calculation by applying the *hourly approach*. By applying the SEA method emission factor, the total annual emission value is characterized by a percentage error of less than 1% compared with the value calculated by applying the *hourly approach.* The allocation between emissions from thermal energy consumption and heat losses on the distribution network varies. As anticipated in section 3.2.4, the emission value associated to network thermal losses in the SEA method considers annual percentage losses (8%). The incidence of losses on total emissions is therefore lower for users characterized by an exclusive winter period heat load profile like in Politecnico di Torino case study.

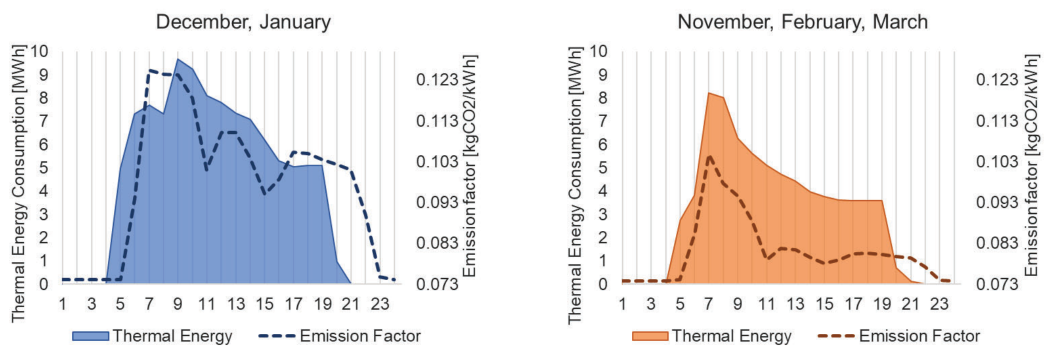

Figure 7. Hourly variation of average daily thermal energy consumption of RD (left axis) and variation of DHS emission factor (right axis).

Figure 9 illustrates the average profile of a typical daily thermal energy consumption at Politecnico di Torino, along with the EF trend shown in dashed lines. The hourly emission factor fluctuations depend on the usage patterns of other DHS users, and therefore the need for backup boilers. These graphs display a similar trend, with a noticeable deviation towards the morning hours. It may be inferred that the Politecnico di Torino begins heating operations earlier and terminates the early in contrast to the average schedule of users.

5. Discussion

This paper presents a new methodology for calculating the hourly variation of CO_2 emissions of DHS, specifically in the case of combined cycle cogeneration plants. A new methodology that enables the calculation of emission factors on an hourly basis and as well as a simplified annual method (SEA method) is presented and compered to existing methodologies. The methodologies described are applied to a representative case study of a tertiary DHS user. The case study selected is Politecnico di Torino. The total CO_2 emissions calculated using the three different methodologies showed a wide variability in the results. In particular, the two methodologies currently in use present two very contrasting results varying from values above that of natural gas to zero values. The need to find an alternative method is therefore confirmed. The emission value obtained with the more accurate hourly analysis is close to the annual value and the error il negligible. The application of the hourly methodology requires knowing the hourly operating data of the generation plants and the hourly heat load of the user. If the user's hourly consumption data is not available, a methodology applicable to tertiary users is proposed to evaluate the user thermal needs. Therefore, SEA method can be used to calculate the total emissions of a structure if thermal energy consumption data has a yearly approximation or if it is not possible to access the hourly generation data of the DHS. SEA method is a good solution in defining total annual emissions, but as compared to the hourly approach it does not allow for a correct allocation of emissions between emissions due to thermal network losses and effective consumption, therefore one unresolved issue is the allocation of distribution thermal losses. At a regulatory level, it is unclear to whom to attribute the value of losses and in what period (annually or in the period of use only). Furthermore, since it can be challenging to ask local entities to conduct deep and complex analyses to determine their CO_2 emissions, it would be beneficial to require DH companies to include this information on bills. These future developments will help to improve the accuracy of CO_2 emissions calculations for users connected to DHS.

The hourly analysis has also highlighted opportunities for improvement in reducing CO_2 emissions. Knowing the hourly variation in emission factor due to the use of different generators, different energy consumption behavior could be motivated to reduce their emissions. For example, users may choose to adjust their energy demand during hours of less use, or install energy storage systems, to store energy when emissions are low and use it when emissions are high. These approaches could contribute to reducing the overall CO_2 emissions during the transition phase towards a complete decarbonization of energy sources. These analyses will become obsolete when DHS will become completely fossil fuel free.

The integration of hourly analysis of both electrical and thermal energy will become increasingly significant as renewable energy sources continue to grow in importance. Future developments should address this challenge by combining the hourly emission factors for both thermal and electric energy sources. This will enable the development of smarter storage and distribution systems for both thermal energy and electricity, ultimately leading to more sustainable and efficient energy use.

Nomenclature

CC CHP Combined Cycle

CHP Combined Heat and Power Plant

DHS District Heating Systems

E electrical power, MW

E_{CHP} ($\overline{\overline{E_{CHP}}}$) electrical power (energy) produced in CHP and delivered, MW $(kWh/year)$

EF emission factor

ES energy Signature

F fuel inlet power, MW

F_i ($\overline{\overline{F_i}}$) fuel inlet power (energy) used for each energy source *i*, MW $(kWh/year)$

F_{CC} ($\overline{\overline{F_{CC}}}$) natural gas fuel inlet power (energy) of Combined Cycle Plant, MW $(kWh/year)$

$f_{i,F}$ energy source *i* EF referring to fuel inlet energy, kg_{CO_2}/kWh

$f_{i,H}$ energy source *i* EF referring to thermal energy produced, kg_{CO_2}/kWh

f_{NG} natural gas EF, kg_{CO_2}/kWh

f_{el} electrical energy EF, kg_{CO_2}/kWh

$f_{CC,H}$ CC CO_2 EF referring to thermal energy produced, kg_{CO_2}/kWh

$\overline{f_{DHS,HE}}$ annual DHS CO_2 EF referring to total utilised energy, kg_{CO_2}/kWh

$f_{DHS,H_{del}}$($\overline{f_{DHS,H_{del}}}$) hourly (annual) DHS CO_2 EF referring to utilised thermal energy, kg_{CO_2}/kWh

$f_{DHS,H_{gen}}$($\overline{f_{DHS,H_{gen}}}$) hourly (annual) DHS CO_2 EF referring to thermal energy produced, kg_{CO_2}/kWh

$f_{DHS,losses}$ hourly DHS CO_2 EF of losses, kg_{CO_2}/kWh

$f_{DHS,cons}$ hourly DHS CO_2 EF of user's thermal consumption, kg_{CO_2}/kWh

H ($\overline{\overline{H}}$) thermal power (energy) produced by Combined Cycle Plant, MW $(kWh/year)$

H_i ($\overline{\overline{H_i}}$) thermal power (energy) produced by generator i, MW $(kWh/year)$

H_{gen} ($\overline{\overline{H_{gen}}}$) total thermal power produced, MW $(kWh/year)$

H_{losses}($\overline{\overline{H_{losses}}}$) losses thermal power (energy) in the distribution network, MW $(kWh/year)$

H_{del} ($\overline{\overline{H_{del}}}$) thermal power (energy) delivered to the user, MW $(kWh/year)$

$H_{s_{daily}}$ user's daily thermal energy consumption, kWh

IBB integration and Back-up Boiler

L_{hh} hour load

$p\%$ ($\overline{\overline{p\%}}$) hourly (annual) percentage thermal distribution losses, %

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RD reference days

STO storage system

TEC thermal Energy Consumption

K cogeneration gain

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