Evaluating the Emissions of the Heat Supplied by District Heating Networks through A Life Cycle Perspective

Francesco Neirotti [1,*] **, Michel Noussan** [2] **and Marco Simonetti** [1]

[1]   Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy;
       marco.simonetti@polito.it
[2]   Fondazione Eni Enrico Mattei, Corso Magenta 63, 20123 Milano, Italy; michel.noussan@feem.it
*   Correspondence: francesco.neirotti@polito.it

Abstract: The Life Cycle Assessment methodology has proven to be effective in evaluating the impacts of goods production throughout their life cycle. While many studies are available on specific products, in recent years a growing interest is related to the analysis of services, including energy supply for final customers. Different LCA evaluations are available for electricity, while the heating and cooling sector has not yet been properly investigated. The objective of this study is the analysis of the specific impacts of the heat supplied to the final users connected to a district heating system, in comparison with traditional individual natural gas boilers, which represent the baseline heating solution in several urban contexts in Europe. The results show that the comparison is heavily dependent on the allocation method used for combined heat and power plant production. District Heating impact on heat supplied to the users can vary from 0.10 to 0.47 kg_{CO_2eq}/kWh, while distributed natural gas boilers present an overall impact equal to 0.27 kg_{CO_2eq}/kWh.

1. Introduction

The current energy systems are increasingly complex, as multiple generation and distribution technologies exist to provide the energy required by the final users. In particular, the heating and cooling energy sector, which is responsible of a large share of Greenhouse Gases (GHG) emission in Europe (EU) [1], is expected to radically change in the upcoming years. Therefore, proper studies to compare the performance of alternative solutions are of interest, to support the energy planners with evidence of the impacts and the efficiency of different solutions. The Life Cycle Assessment (LCA) methodology is widely applied to evaluate the impacts of goods production throughout their life cycle, and to asses the environmental sustainability of products, goods, food, etc. [2]. Moreover, LCA is a useful tool in order to asses and quantify the achievement towards the Sustainable Development Goals (SDGs) set by the United Nations [3–5] which are working as drivers for international green and clean policies.

The LCA approach has been initially developed for the assessment of the production of goods as in [5–7], but thanks to the flexibility of its methodology, in recent years there is a growing interest in applying it to a range of services as well. Different examples exist of studies that have applied LCA approach to the electricity generation and goods. In [8,9], the authors performed a review on the different LCA studies about electricity generation for traditional and renewable sources respectively, while the authors of [10] analysed the environmental impact evolution of the Brazilian electricity generation system from 2016 to 2026. In [11,12], electricity production from biomass is analysed,

and environmental benefits and critical processes, like biomass transportation, are highlighted. Moreover, other authors, as in [13,14], have already proven the importance of the LCA approach in estimating the advantages of different energy technologies. Manufacturing, fuel extraction and transport [15–17] can play an important role in determining the overall impact of an energy technology.

However, less attention has been paid to the heating sector: some studies have compared heat pumps and gas-fired boilers [18] or to biomass based heating systems [16], while others have been focused on solar systems [19]. When it comes to district heating (DH) systems, few studies have addressed the LCA of the heat supplied to the users through DH networks. Eriksson et al. [20] have compared the use of biomass and natural gas as fuels in DH systems, while others have been focused on single technologies [21], the network construction [22] or the used fuel as in [23]. A comparison with traditional distributed boilers, which represent the standard solution in multiple countries, has not currently being evaluated in the literature.

The aim of this work is to help filling this gap, by providing a study on the LCA impact of heat generation in an existing large-scale district heating system, in comparison with the distributed natural gas boilers, which are the reference solution for buildings heating in the region. The results can support policy makers in evaluating the effectiveness of DH systems in large urban contexts.

1.1. Turin District Heating System

This study is based on the real annual values obtained from the operational data of the city of Turin. The city is located in the northwest of Italy and present a continental climate with humid summer and cold winter with around 2600 heating degree days [24]. Moreover, it is associated to a climate area *Cfb*, based on the Kopper–Geiger climate classification [25]. Turin has a large-size district heating network (reported in Figure 1) which provides heat more then 50% of the overall city heating volume. The heat produced in the system is generated by high-efficiency natural gas-fired combined cycles power plants. The Turin district heating system is currently the largest system in Italy, and among the largest systems in Europe. It supplies heat to ~62 million m^3 of buildings volume, with 6455 substations, and it has a total network extension of ~568 km [26].
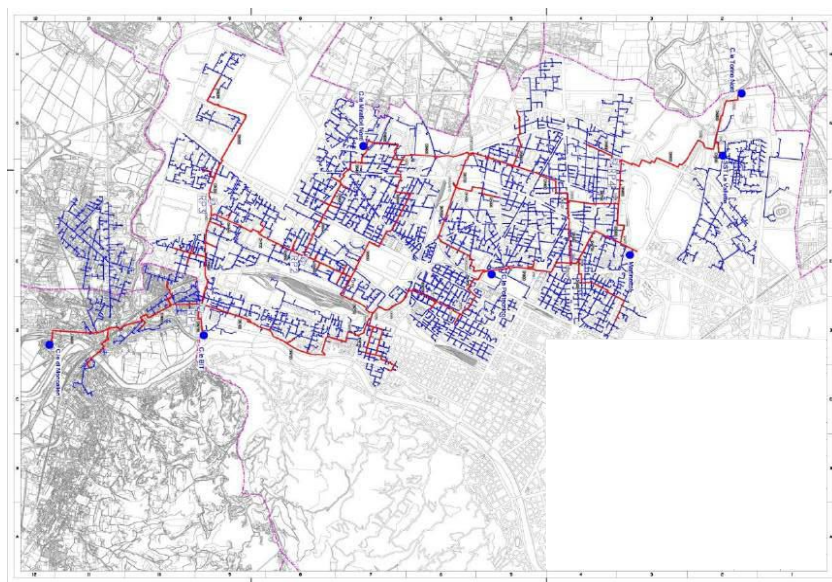

Figure 1. Turin district heating (DH) network extension. Reproduced from [27,28], IREN 2018.

The largest part of the energy supply is produced by three combined heat and power (CHP) plants located in Turin and Moncalieri [29], which provide approximately 95% of the annual thermal energy demand [26,30] with an average overall efficiency equal to 74% [26]. Integration gas-fired boilers and thermal storage systems are used during peak hours and to optimise the overall system performance.

Thanks to the use of CHP plants, the DH network has always been considered more efficient than the separate production of heat and electricity, and an additional advantage in comparison with individual gas boilers is related to the higher effectiveness in filtering pollutants emissions, especially NO_X.

The network is operated at 120–95 °C supply and 80–45 °C return temperatures, depending on the month of the year. Pumping stations are installed at each thermal plant, and different booster pumping groups are located along the network to ensure acceptable pressure levels in all the network branches. The main characteristics of the DH system components are listed in Table 1.

Table 1. Main parameters of Turin DH system. Reproduced from [26,29], AIRU 2018.

Production Plant	Cogenerative Power Plant		Integration Boiler	Storage
[-]	MWe	MWt	MWt	m^3
Torino Nord	400	220	340	5000
Monacalieri	800	520	141	-
BIT	-	-	255	2500
Politecnico	-	-	255	2500
Martinetto	-	-	-	5000

2. Methods

The methodology of LCA is defined in detail in the norm ISO 14040/44 [31], where all the specific rules and the main hypotheses are illustrated. It is composed of 4 main sections:

1. Definition of Goal and Scope
2. Inventory analysis phase
3. Impact assessment phase
4. Interpretation of the result

The first three sections are related to the input data and the hypotheses that are chosen for each study.

2.1. Definition of Goal and Scope

The scope of this study is to estimate the life cycle impact of 1 kWh of thermal energy produced in the Turin DH system and supplied to the final users, in comparison with 1 kWh generated in households by individual natural gas boilers (GB). Concerning the system boundaries, we consider the entire supply chain, from raw materials to the energy delivered to users. No decommissioning or recovery processes have been considered, due to the long lifetime that makes the end of life impact hard to estimate.

Regarding the DH system, the LCA study is based on the 2017 Turin DH energy balance provided by AIRU [26,28]. Moreover, to slightly simplify the analysis, not all the components of the DH system are considered in this paper. As 94% of the DH thermal energy is provided by CHPs, and even larger shares in some recent years, integration plants are not considered. Moreover, due to difficulties in finding reliable data even pumping stations and storages have not been considered.

As no specific information was available on the origin of building materials, Ecoinvent 3 global average material streams have been used, by considering the steel used for the construction of heat exchangers and piping. Moreover, for materials transformation, we used average manufacturing processes streams or simple material flow (both available in the Ecoinvent 3 database [32]), due to a lack of data about their actual production processes, which have been performed at different stages of network expansions. A lifetime of 25 years has been assumed for CHP plants the heat exchangers and the natural gas boiler. For the piping network, a lifetime of 40 years has been assumed, in accordance with usual hypotheses in similar studies. Moreover, as CHP technology involves multiple outputs, a proper allocation method is needed to associate the impacts on the heat and electricity generation

respectively. The choice of the allocation method is an important aspect, as it can have a significant impact on the results [33]. In this paper, a comparison between two allocation methodologies is conducted to represent the range of variability of the results.

As a single DH substation generally serves one condominium or a group of them, it has been decided to compare the DH solution in comparison with 40 distributed gas boiler, representing a large condominium. As already stated in the introduction, GB represent the reference solution for domestic heating system with many different product and configuration possibilities. For this reason, we have decided to use the already present Ecoinvent stream "market for gas boiler, cut-off, S" instead of a precise configuration. The "market for gas boiler, cut-off, S" represent the amount of materials and energy (from cradle) spent to make a generic 10 kW gas boiler with the main components such as burner, safety valves and water pipes.

2.2. Life Cycle Inventory Analysis

The inventory section contains the different data about streams and materials used in the analysis. The main data at the basis of this study are recapped in Table 2.

Table 2. Material and energy stream used.

Component	Input Data		Output Data	
	Stream	Quantity	Stream	Quantity
CHP Plants Energy Production	Combined-Cycle Plant, 400 MWel	3 unit	CO_2	1.99×10^9 kg
	High Pressure Natural Gas	1.01×10^9 m^3	Thermal Energy	2.17×10^6 MWh
			Electrical Energy	5.66×10^6 MWh
Plant Heat Exchanger	Thermal Energy	2.17×10^6 MWh	Thermal Energy	2.17×10^6 MWh
	Steel	1.18×10^5 kg		
Pipe Network	Thermal Energy	2.17×10^6 MWh	Thermal Energy	1.77×10^6 MWh
	Steel	7.33×10^7 kg		
	Polyurethane Foam	5.86×10^6 kg		
	Polyethylene	9.87×10^6 kg		
User Heat Exchanger	Thermal Energy	1.77×10^6 MWh	Thermal Energy	1.59×10^6 MWh
	Steel	2.96×10^6 kg		
Gas Boiler	Gas Boiler, 10 kW	40 unit	CO_2	4.97×10^4 kg
	High Pressure Natural Gas	2.53×10^4 m^3	Thermal Energy	2.46×10^2 MWh

As already said, the energy generation and natural gas consumption data for the DH system have been taken from the most recent operation data available (year 2017), as well as the energy balance data: so, they can be considered as primary data (i.e., directly referred to the plant that is being analysed). In addition, since the consumed gas and the output thermal energy are known, the efficiency is implicitly considered in the calculation. Concerning the CHP plant construction and natural gas boilers, already available streams from Ecoinvent 3 database have been used. The power plants' heat exchanger is a shell-and-tube one and it has been characterised with its nominal parameters (water temperature difference, type of materials, heat transfer coefficient, external dimension, etc.) by a direct interview with the operator of the plants. Starting from these data, an estimation of the steel amount has been performed by sizing the heat exchanger following the thermodynamic laws and EN10255 prescriptions [34]. In particular, having the nominal temperature difference and the nominal U value W/(m^2 K) the needed surface has been estimated with Equation (1),

$$P = UA\Delta_{LM} \tag{1}$$

where P [W] is the rated thermal power (reported in Table 1), U is the heat transfer coefficient equal to 2300 [W/m^2 K], Δ_{LM} is the mean logarithmic temperature difference, and A [m^2] is the heat exchanger surface. Knowing the pipes and vessel dimensions and thicknesses (retrieved from EN10255 and direct interview), it is possible to estimate the total amount of steel needed for the heat exchangers construction. Finally, it has been used a heat exchanger efficiency $\eta_{HXplant}$ = 1.0 because the output

thermal energy reported in the AIRU report already take into account the heat exchanger efficiency (See Table 3 where the same thermal energy output is reported for the CHP plant and for the Plant Heat exchanger). In Table 3 are reported the main used parameters.

Table 3. Main parameters for plant heat exchanger sizing.

Plant	A [m²]	Total Pipes Length [m]	Pipe Thickness [m] EN10255	Pipe Linear Weight [kg/m] EN10255	Shell Thickness [m] EN10255	ρ Steel [kg/m³]	ΔT_{LM} [°C]
Moncalieri	2690	31.3×10^3	3.2×10^{-3}	2.44	6.3×10^{-3}	8×10^3	84.2
Torino Nord	1140	13.2×10^3					

Instead, the users' plate heat exchanger has been sized and designed based on different catalogues from producers [35,36], where typical weight, dimension, number of plates, and materials have been selected. Table 4 recaps the main parameter used for sizing. The heat exchanger are mainly made by steel and presents 150 flat plates to drive the heat exchange between the DH water (120–90 °C) and the heating system water (80–40 °C). Using the rated power and the needed surface (calculated with Equation (1)), product composition and typology has been selected from the catalogues. An overall thermal efficiency of 0.9 has been used.

Table 4. Main parameters for substation heat exchanger sizing.

	# Substation	Nominal Power [kW] Single Substation	A [m²] Single HX	U [W/(m²K)]	$DeltaT_{LM}$ [°C]	Number of Titanuim Plate Single HX	Efficiency [-]
User HX	6455	400	6	1500	44.8	150	0.9

Finally, pipes diameters, insulation thicknesses and materials have been designed based on the LOGSTOR catalogue available on the website [37], considering the characteristics of the network. The DH present different pipe diameters across the network. As the precise extension per each diameter is a difficult information to retrieve, an average value of 400 mm as outer diameter has been used (catalogue range: 1200–20 mm). The pipe is composed of three layers: a steel body, a polyuretane foam insulation layer and an outer chasing in polyethylene and the linear mass for the 400 mm pipes is equal to 79 kg/m. As reported in Table 5, the mass of the different layers has been estimated starting from the thicknesses and material density of the different layers. Moreover, a thermal efficiency equal to 0.81 [26] has been used for the piping network.

Table 5. Main parameters for pipe sizing.

	Steel Body	Insulation-Polyurethane Foam	Outer Chasing-Polyethylene	
	ρ = 8000 kg/m³	ρ = 70 kg/m³	ρ = 940 kg/m³	
Layer Thickness	6.4	102	5.7	mm
Material Volume	9.2×10^3	8.4×10^4	1.1×10^4	m³
Linear Mass	65.0	5.0	9.0	kg/m

Moreover, we did not consider the impact of network construction, due to the difficulty of finding reliable data. It is worth mentioning that for all manufacturing processes of the pipes and the heat exchangers, impacts have been estimated with the Ecoinvent 3 average manufacturing processes streams. As reported in Table 2, high pressure natural gas stream has been selected for both the gas boiler and CHP plant components in order to keep the same energy source for the two technologies.

The GB scenario, partially introduced in paragraph Section 2.1, takes into account 40 distributed gas boiler of 10 kW as rated power (total of 400 kW, as the DH substation) with an overall thermal efficiency of 0.9. In order to fairly compare the GB solution with the DH one, the thermal energy output of the 40 units as been equal to the average thermal energy delivered from a single substation. This value has been retrieved by dividing the overall thermal energy delivered by the DH system (2.17×10^6 MWh) to the total number of substation (6455). Then, using a LHV_{Gas} = 39 MJ/m³ and an

efficiency $\eta_{GB} = 0.9$, the overall gas consumption has been calculated together with the CO_2 emissions, following the stoichiometric reaction (1 mole of CO_2 per mole of CH_4). Again, the input data are reported in Table 2.

To sum up, we can consider energy balance data (gas input, electricity production, thermal energy delivered, etc.), CO_2 emissions and materials for the plant heat exchanger as primary data, while considering plant and boilers construction, manufacturing processes and material extraction as secondary data.

2.3. Life Cycle Impact Assessment

The LCA analysis has been conducted with OpenLCA software [38] and the Life Cycle Impact Assessment (LCIA) method used to assess the values of LCA indicators is the CML (v4.4 2015) method developed by the Leiden University [39]. In this method, a set of impact categories and and characterisation method have been linked to the Ecoinvent stream database [40] in order to effectively manage all the streams during the LCIA phase. In particular, for the Global Warming category, global warming potential (GWP) factors by IPCC are used to calculate the impact. Moreover, different time horizon are available (20,100,500 years). As recommended in [41], this work use the 100 year time horizon GWP_{100y}. The detailed method and specification are reported in [41], while the flows database is freely downloadable from [42].

The different impact categories available are listed in Table 6, but the focus of our analysis is on the "Climate Change" impact category. Further information about the method can be found in [43,44]. Moreover, in the first column of Table 6 are reported the different SDGs for which the impact categories are relevant, to further describe the implications in the perspective on global sustainable goals [5].

Table 6. CML impact categories and correlated Sustainable Development Goals (SDGs).

SDG		Impact Category	Reference Unit
15	AP	Acidification Potential	kg SO_2 eq.
13	CC-100y	Climate Change-GWP 100	kg CO_2 eq.
13, 15	DAR	Depletion of Abiotic Resources	kg antimony eq.
13, 15	DAR-Fossil	Depletion of Abiotic Resources - Fossil Fuels	MJ
14, 15, 6	Eutroph.	Eutrophication	kg PO_4 eq.
14, 6	FwAEcotox.	FreshWater Aquatioc Ecotoxicity	kg 1,4-dichlotobenzene eq.
3	Htox	Human toxicity	kg 1,4-dichlotobenzene eq.
14	MAEcotox.	Marine Aquatic Excotoxicity	kg 1,4-dichlotobenzene eq.
13, 15	OLD	Ozone Layer Depletion	kg CFC-11 eq.
3	Pox	Photochemical Oxidation	kg ethylene eq.
15	Tecotox.	Terrestrial Ecotoxicity	kg 1,4-dichlotobenzene eq.

An additional aspect to be discussed is the allocation factor of the energy output. As already stated, the DH system considered in this study is based on CHP units that are producing both heat and power outputs, and proper allocation factors are needed to estimate the impact associated to the heat supplied to final users. In [33], different allocation factors methodologies are reported and evaluated, and two of them are used in this study: the Energy Methodology (EN) and the Exergy Methodology (EX). The former is based on the idea of allocating the impacts depending on the amount of energy produced for each type, i.e., without differentiating the higher "*quality*" of electrical energy (*E*) with respect to thermal energy (*Q*). The electricity and heat factor α_E and α_Q can be calculated as follows.

$$\alpha_E = E/(E+Q) \tag{2}$$

$$\alpha_Q = Q/(E+Q) \tag{3}$$

The two factors are then multiplied for the overall emissions in order to allocate the overall CO_2 emission [kg_{CO_2eq}] to the different energy output. On the other hand, the Exergy approach has the

aim of giving a different weighting factor to power generation, which has a higher value given the possibility of converting it further to heat. In particular, for electricity, the exergy coincides with the energy, while for the heat, it is related to the delivered temperature. Therefore, the two factors are calculated as follows,

$$\alpha_Q = \frac{Q(1 - T_{ref}/T_Q)}{E + Q(1 - T_{ref}/T_Q)} \tag{4}$$

$$\alpha_E = 1 - \alpha_Q \tag{5}$$

where T_{ref} is the reference temperature, equal to 298 K, while T_Q is defined as

$$T_Q = \frac{T_S - T_R}{log(T_S/T_R)} \tag{6}$$

where T_S and T_R are, respectively, the supply and return temperatures of the DH network in Kelvin (393–353 K). The choice of the Exergy methodology is in accordance to the idea that in traditional power plants (at the time of the construction of the DH system under analysis) the electricity generation was the priority, with heat being a by-product that was usually dissipated and, for this reason, the allocation factor for the heat is much lower with respect to the electricity one. In the current energy transition, the strong penetration of renewable technologies for power generation has changed this perspective. Thus, we believe that a comparison of these two methods may be of use for the reader to compare alternative approaches. The used allocation coefficients are reported in Table 7.

Table 7. Allocation Factor for the two different methodologies.

	Energy Method	**Exergy Method**
α_E	0.72	0.94
α_Q	0.28	0.06

These two methods have been chosen because their allocation requires no additional external hypothesis, such as reference efficiency parameters, which can have a significant impact on the results. In the case of the Power Bonus Method, which is defined in the European and Italian legislation, the reference efficiency for natural gas power plants results in a 100% allocation of resources and impacts on electricity. This would lead to a virtually carbon-free heat, which is not a meaningful result for this study. These aspects are described in greater detail in [33].

3. Results and Discussion

The output of the LCA process has been divided by the useful heat and electricity generated by the DH system, with a proper allocation in the CHP unit. The same study has been performed on small-size distributed natural gas boilers, to compare the impacts of the two alternative solutions.

In Figure 2, the Climate Change impacts calculated for the heat supply are reported, in terms of kg_{CO_2eq} over useful kWh divided in the different construction and operation phases of the system. The results show an overall impact for individual gas boilers (GB) equal to 0.27 kg_{CO_2eq}/kWh, while for DH equal to 0.47 and 0.10 kg_{CO_2eq}/kWh for the Energy and Exergy methodologies, respectively. As expected, the main contribution derives from the natural gas combustion, followed by the gas import (and distribution). It is important to highlight that the system construction is irrelevant for both technologies in accordance with the works in [15,16], which has the same results for biomass boilers and air conditioning unit with gas boiler, and thus the common practice of considering operational data when evaluating climate change impacts is a good evaluation (see Figure 3 for minor contribution share division).
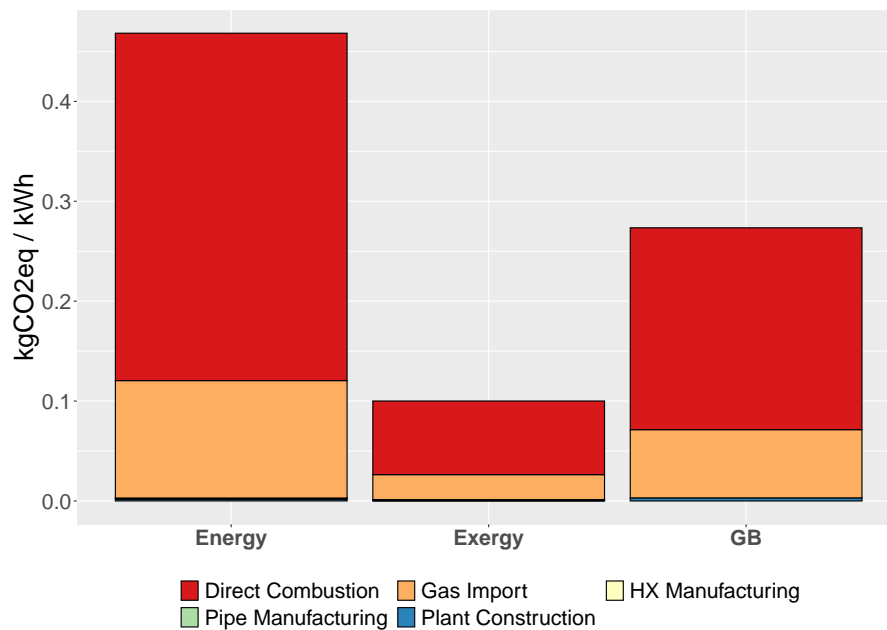
Figure 2. Specific emissions for DH with allocation methods and for GB.
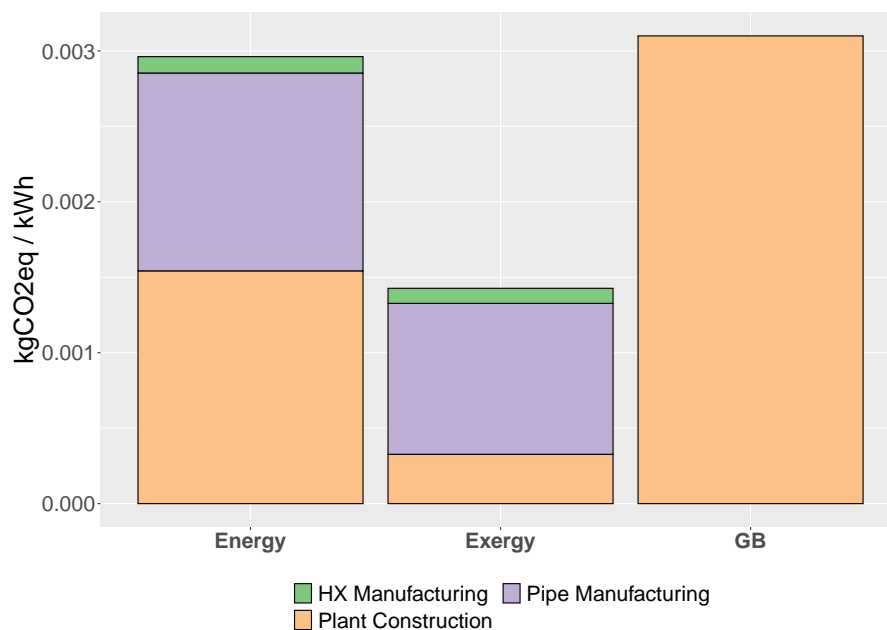

Figure 3. Specific emissions for DH with allocation methods and for GB-Detail of minor contribution.

Another main outcome of this analysis is the dramatic impact of the allocation method on the final results, as, based on this choice, the impact of DH heat can be lower or higher than the individual natural gas boilers. In this case study, a wide gap is noticeable between energy and exergy methodology. The second one boosts the competitiveness of CHP giving to heat production less importance, presenting the DH as a key technology in lowering the emission factor of the heat supply. On the contrary, the energy methodology suggests a less interesting emission factor for heat supplied by DH, which is much higher than the individual boilers solution. Moreover, different allocation methods can be affected not only by the energy production, but also by other variables such as, in the case for the exergy method, the reference temperature considered or the definition of the reference energy system in the alternative generation method. Other methods are also strongly dependent on the specific assumptions that are taken on

reference efficiencies. The power bonus method, which is not considered in this study, is strongly affected by the choice of the reference parameters that are used.

It is also important to remark that we are comparing DH with high-efficiency gas boilers (with average annual efficiency of ~90%). However, old and inefficient boilers are still operating in cities with poor combustion/emission control systems and sometimes running on lower quality fossil fuels like diesel or fuel oil. Nevertheless, we believe that our assumption is a fair choice for the average boiler characteristics of the dwellings in Turin, especially considering that old boilers are being gradually phased out following the EU and Italian directives.

Finally, it is interesting to notice the significant impact of the natural gas import: it is produced not only by the CO_2 emitted for construction, but also from the CH_4 leakage that has an important impact on climate change as its Global Warming Potential (GWP; i.e., its impact measured as a ratio over the emission of the same amount of CO_2) is equal to 25. This aspect should be carefully considered when planning the infrastructure and the gas import: strong actions to limit the leakage rates can significantly lower the overall impact of different gas-based technologies.

This aspect is well presented in Figure 4, where the impacts are represented as if all the gas was provided from Germany (DE), the current Italian mix (ITA mix) and Russia (RU). The different streams are present present in the Ecoinvent 3 database.
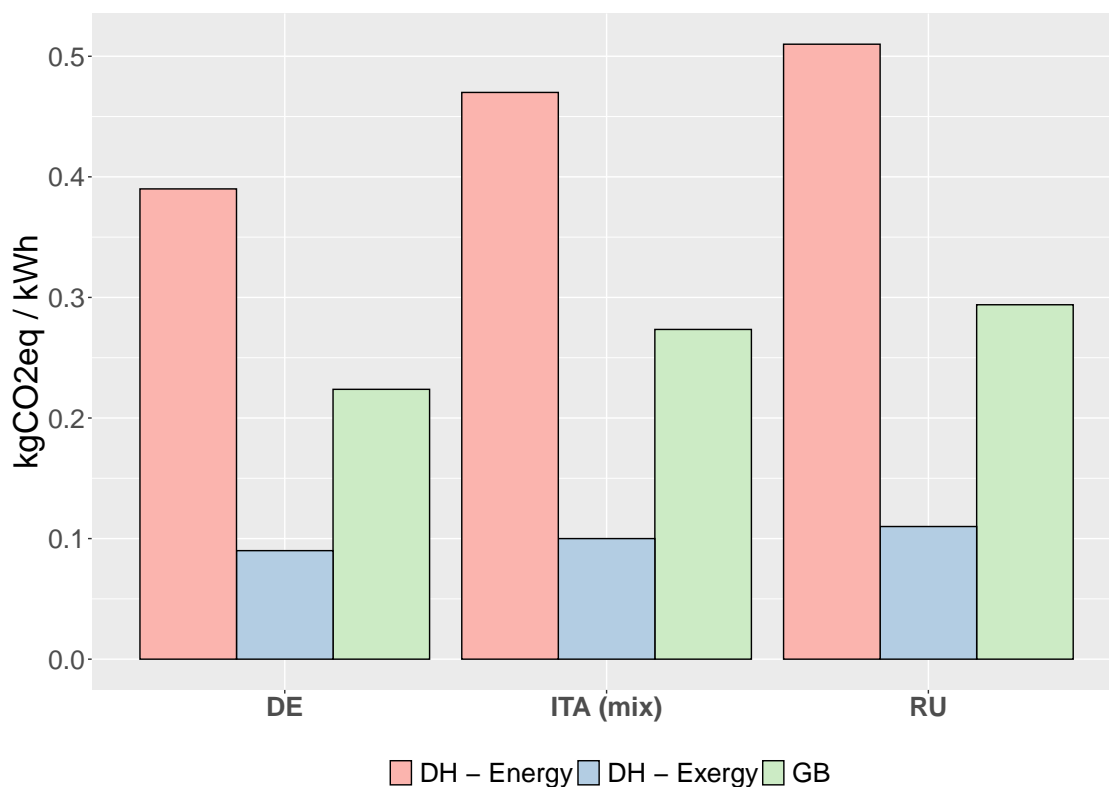

Figure 4. DH specific impact with different gas supplier.

While this analysis has been mostly focused on climate change impacts, some information can be provided also on the other impacts to give the reader a comprehensive overview on the different environmental impacts. The main results of the LCA analysis with respect to all the impacts are reported in Table 8, where all the impacts are expressed with reference to a unit of heat supplied to the final users (i.e., 1 kWh$_t$). The majority of the impacts shows comparable results for DH and individual boilers, with the impact of the allocation methodology that is strongly affecting the comparison between the systems.

Figure 5 shows additional insights, by representing the weight of the different phases calculated by the LCA analysis for all the environmental impacts listed in Table 8. The phases that are considered are both related to the system construction (heat exchanger manufacturing, pipes manufacturing and plant construction) and to its operation (direct combustion of natural gas and natural gas import and distribution).
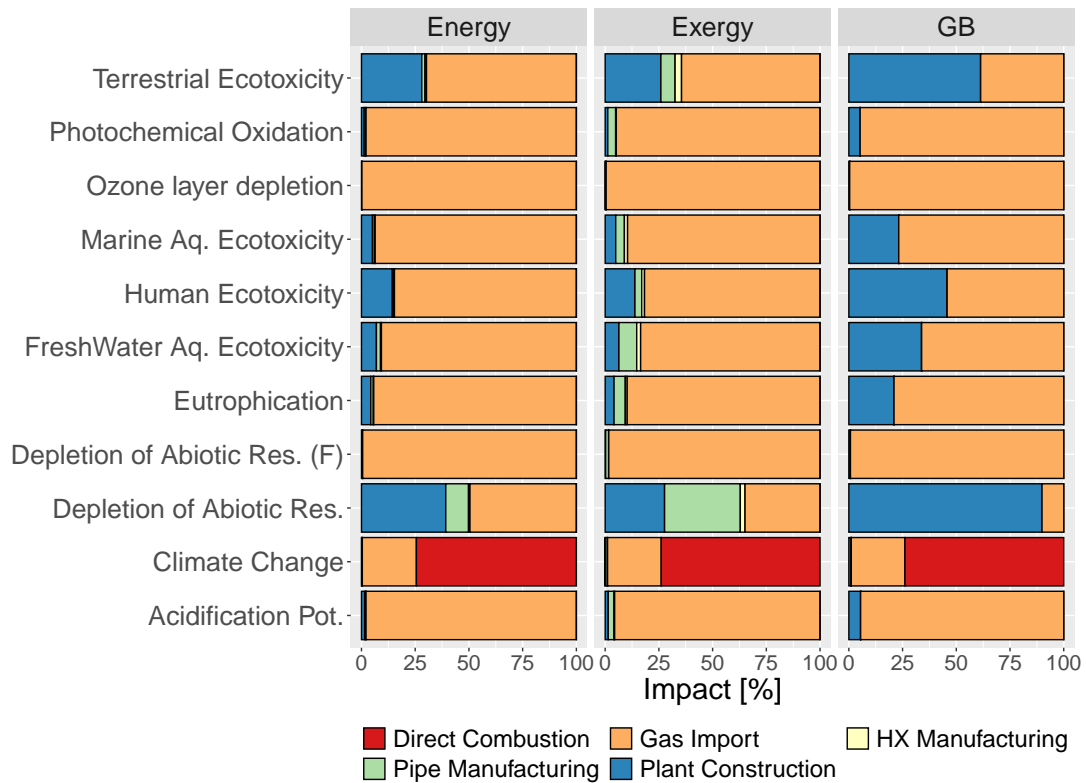

Figure 5. Summary of impacts as a percentage of the total.

Table 8. The overall impact for the different categories and for the different allocation methods.

SDG	Impact Category	Reference Unit	Energy	Exergy	Gas Boiler
15	Acidification Potential	kg SO$_2$ eq.	8.76×10^4	1.90×10^4	5.27×10^3
13	Climate Change-GWP 100	kg CO$_2$ eq.	4.67×10^{-1}	9.97×10^{-2}	2.73×10^{-1}
13, 15	Depletion of Abiotic Resources	kg antimony eq.	7.85×10^{-8}	2.36×10^{-8}	2.23×10^{-7}
13, 15	Depletion of Abiotic Resources-Fossil Fuels	MJ	7.44	1.60	4.33
14, 15, 6	Eutrophication	kg PO$_4$ eq.	1.07×10^{-4}	2.39×10^{-5}	7.46×10^{-5}
14, 6	FreshWater Aquatioc Ecotoxicity	kg 1,4-dichlotobenzene eq.	2.38×10^{-2}	5.49×10^{-3}	1.90×10^{-2}
3	Human toxicity	kg 1,4-dichlotobenzene eq.	4.38×10^{-2}	9.63×10^{-3}	3.97×10^{-2}
14	Marine Aquatic Excotoxicity	kg 1,4-dichlotobenzene eq.	8.23×10^1	1.82×10^1	5.83×10^1
13, 15	Ozone Layer Depletion	kg CFC-11 eq.	8.17×10^{-8}	1.74×10^{-8}	4.75×10^{-8}
3	Photochemical Oxidation	kg ethylene eq.	5.71×10^{-5}	1.25×10^{-5}	2.43×10^{-5}
15	Terrestrial Ecotoxicity	kg 1,4-dichlotobenzene eq.	4.50×10^{-4}	1.03×10^{-4}	4.72×10^{-4}

Gas import is the main contributor in almost all the considered impact categories. It is also notable the effect of the allocation factor: in categories from marine aquatic ecotoxicity to eutrophication, as well as in depletion of abiotic resources, the weight of the different phases vary between energy and exergy method (e.g., pipe manufacturing weights 10.6% and 35.2% with energy and exergy, respectively, in the depletion of abiotic resources). The share variation is due to the fact that allocation factors are applied only to the components that are related both to electricity and heat, i.e., direct combustion, gas import and plant construction. Pipe manufacturing and heat exchangers manufacturing are only related to thermal energy and they are thus completely allocated on the heat supply. The plant construction

results the main contributor for terrestrial ecotoxicity and depletion of abiotic resources for gas boilers (GB), while for DH plant the natural gas import results as the major contributor in almost all the categories except for climate change and depletion of abiotic resources. As already said, while these preliminary results give an overview on the different impact categories considered in LCA studies, the focus of this work is limited to climate change impacts.

3.1. Future Developments

This work is a first analysis of the comparison of DH and gas boilers, which has been done by considering some approximations based on reasonable assumptions. A better description of the system, including backup boilers, precise manufacturing of components and network construction emissions should be performed; this would require additional information that are not available at this stage. However, due to their low importance in the final impact the results will probably not show significant variations. Comparisons with other generation technologies and other DH networks could improve the robustness of the results of this study, including the specific impact of network efficiency, fuel utilisation (which can play an important role as stated in [23] and generation technology. Furthermore, different boiler technologies and efficiency levels could be evaluated to verify a more realistic overview and especially a comparison with heat pumps which in others works shows a reduction of GHG emission around 18% with respect to traditional heating systems [13], in substitution to GB, could be added to the study.

4. Conclusions

This study presents a comparison of the environmental impact of the heat supplied to the final users connected to a natural gas-fired district heating system, in comparison with traditional individual natural gas boilers, which represent the baseline heating solution in several urban contexts. The focus of this research is on specific CO_2 emissions, which is a parameter that is often used in different analyses. The specific impacts have been determined using the LCA analysis, to consider the entire life cycle of the components. The main results are recapped in Table 9.

Table 9. Specific impacts—values for the different allocation method and gas import streams

	DE			ITA			RU			
	EN	EX	GB	EN	EX	GB	EN	EX	GB	
Specific Impact	0.39	0.09	0.22	0.47	0.10	0.27	0.51	0.11	0.29	kg_{CO_2eq}/kWh
	Variation [%]		+21%	+11%	+22%	+31%	+22%	+31%		With respect to the DE case

The results of our work show a specific emission equal to 0.47 and 0.10 kg_{CO_2eq}/kWh for district heating with Energy and Exergy methodologies, respectively, against the 0.27 kg_{CO_2eq}/kWh of the distributed gas boiler. The CO_2 emitted during the combustion is the main contributor to the overall impacts of both technologies. In fact, it accounts for ~74% of the overall emission value. However, gas infrastructure accounts for an important share too (~25%) and it shows a main role in all the other specific impacts as reported in Table 5. It can heavily influence the results, increasing, for example, the specific impact from 0.39 to 0.51 kg_{CO_2eq}/kWh (marking a +31%) for DH specific emission calculated with the energy methodology. For this reason, careful evaluations must be considered in gas import strategies and policy planning. On the contrary, commissioning and construction phases contributions are almost irrelevant to the balance. This suggests that the common practice of relying on operational data and neglecting the impact of the construction phase seems to be a reasonable approach. However, this is true for CO_2 emissions but not for other environmental impacts (e.g., depletion of abiotic resources), for which the construction phase of the different components has a non-negligible effect.

An additional aspect to be highlighted is that the specific emissions of the DH system are highly dependent on the CHP allocation method that is chosen, as the results show a variation from +72%

to −60% with respect to individual gas boilers. This large variation is related to the perspective with which cogeneration is considered, i.e., the relative importance which is given to heat and power generation in CHP systems. This behaviour is reflected also from the results of the other impact categories, where the allocation factor produces a variation of the final results. Thus, an appropriate choice of the allocation factor is of paramount importance, and this choice should be in line with the aim of the analysis and taken to account when interpreting the results.

Abbreviations

The following abbreviations are used in this manuscript.

CHP	combined heat and power
DH	district heating
EN	energy allocation method
EX	exergy allocation method
GB	gas boilers
GWP	global warming potential
LCA	life cycle assessment

References

1. Commission, E. *Support Activities and Projects about Heating and Cooling Sector*; Technical Report; Europen Union: Maastricht, The Netherlands, 2016. [CrossRef]
2. Caldeira, C.; Cobalea, H.B.; De Laurentiis, V.; Sala, S. *Review of Studies on Food Waste Accounting at Member State Level*; Number January 2020; Europen Union: Maastricht, The Netherlands, 2019. [CrossRef]
3. United Nations, UN Website-SDGs. Available online: https://sdgs.un.org/ (accessed on 31 August 2020).
4. Sala, S.; Castellani, V. The consumer footprint: Monitoring sustainable development goal 12 with process-based life cycle assessment. *J. Clean. Prod.* **2019**, *240*. [CrossRef] [PubMed]
5. Sala, S.; Benini, L.; Beylot, A.; Cerutti, A.; Corrado, S.; Crenna, E.; Diaconu, E.; Sinkko, T.; Pant, R. *Consumption and Consumer Footprint: Methodology and Results*; Europen Union: Maastricht, The Netherlands, 2019.
6. Castellani, V.; Beylot, A.; Sala, S. Environmental impacts of household consumption in Europe: Comparing process-based LCA and environmentally extended input-output analysis. *J. Clean. Prod.* **2019**, *240*. [CrossRef] [PubMed]
7. Sala, S.; Crenna, E.; Secchi, M.; Sanyé-Mengual, E. Environmental sustainability of European production and consumption assessed against planetary boundaries. *J. Environ. Manag.* **2020**, *269*. [CrossRef] [PubMed]
8. Varun.; Bhat, I.; Prakash, R. LCA of renewable energy for electricity generation systems—A review. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1067–1073. [CrossRef]
9. Turconi, R.; Boldrin, A.; Astrup, T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. *Renew. Sustain. Energy Rev.* **2013**, *28*, 555–565. [CrossRef]
10. Barros, M.V.; Piekarski, C.M.; De Francisco, A.C. Carbon footprint of electricity generation in Brazil: An analysis of the 2016–2026 period. *Energies* **2018**, *11*, 1412. [CrossRef]
11. Shafie, S.; T.M.I.Mahlia.; Masjuki, H.; Rismanchi, B. Life cycle assessment (LCA) of electricity generation from rice husk in Malaysia. *Energy Procedia* **2012**, *14*, 499–504. [CrossRef]
12. Guerra, J.P.M.; Coleta, J.R.; Arruda, L.C.M.; Silva, G.A.; Kulay, L. Comparative analysis of electricity cogeneration scenarios in sugarcane production by LCA. *Int. J. Life Cycle Assess.* **2014**, *19*, 814–825. [CrossRef]
13. Saner, D.; Juraske, R.; Kübert, M.; Blum, P.; Hellweg, S.; Bayer, P. Is it only CO$_2$ that matters? A life cycle perspective on shallow geothermal systems. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1798–1813. [CrossRef]

14. Díaz, M.; Rezeau, A.; Maraver, D.; Sebastián, F.; Royo, J. Comparison of the Environmental Impact of Biomass and Fossil Fuels Medium-Scale. In Proceedings of the 16th European Biomass Conference & Exhibition, Valencia, Spain, 2–6 June 2008; pp. 2641–2646. [CrossRef]

15. Shah, V.P.; Debella, D.C.; Ries, R.J. Life cycle assessment of residential heating and cooling systems in four regions in the United States. *Energy Build.* **2008**, *40*, 503–513. [CrossRef]

16. Longo, S.; Cellura, M.; Guarino, F.; La Rocca, V.; Maniscalco, G.; Morale, M. Embodied energy and environmental impacts of a biomass boiler: A life cycle approach. *AIMS Energy* **2015**, *3*, 214–226. [CrossRef]

17. Caserini, S.; Livio, S.; Giugliano, M.; Grosso, M.; Rigamonti, L. LCA of domestic and centralized biomass combustion: The case of Lombardy (Italy). *Biomass Bioenergy* **2010**, *34*, 474–482. [CrossRef]

18. Nitkiewicz, A.; Sekret, R. Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler. *Energy Convers. Manag.* **2014**, *87*, 647–652. [CrossRef]

19. Beccali, M.; Cellura, M.; Longo, S.; Guarino, F. Solar heating and cooling systems versus conventional systems assisted by photovoltaic: Application of a simplified LCA tool. *Sol. Energy Mater. Sol. Cells* **2016**, *156*, 92–100. [CrossRef]

20. Eriksson, O.; Finnveden, G.; Ekvall, T.; Björklund, A. Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion. *Energy Policy* **2007**, *35*, 1346–1362. [CrossRef]

21. Parajuli, R.; Løkke, S.; Østergaard, P.A.; Knudsen, M.T.; Schmidt, J.H.; Dalgaard, T. Life Cycle Assessment of district heat production in a straw fired CHP plant. *Biomass Bioenergy* **2014**, *68*, 115–134. [CrossRef]

22. Fröling, M.; Persson, C.; Svanström, M. LCA Case Studies Life Cycle Assessment of the District Heat Distribution System Part 3: Use Phase and Overall Discussion. *Int. J. Life Cycle Assess.* **2006**, *11*, 437–446.

23. Karlsson, J.; Brunzell, L.; Venkatesh, G. Material-flow analysis, energy analysis, and partial environmental-LCA of a district-heating combined heat and power plant in Sweden. *Energy* **2018**, *144*, 31–40. [CrossRef]

24. Eurostat. *Eurostat-Cooling and Heating Degree Days by NUTS 2 Regions-Annual Data*; Eurostat: Luxembourg, 2017.

25. PVSITES Consortium. D2.2 European Climate Zones and Bio-Climatic Design Requirements; Europen Union: Maastricht, The Netherlands, 2016; pp. 1–31.

26. AIRU—Associazione Italiana Riscaldamento Urbano, Annuario 2018. Available online: https://www.airu.it/annuario-2018/ (accessed on 17 June 2020)

27. IREN Energia IREN—Turin District Heating Extension. Available online: https://associazioneaiden.it/index.php/it/ (accessed on 30 August 2020).

28. AIRU-Associazione Italiana Riscaldamento Urbano. AIRU Website. Available online: https://www.airu.it/ (accessed on 17 June 2020).

29. IREN Energia. Gli Impianti di Cogenerazione e il Teleriscaldamento a Torino. Available online: https://www.irenenergia.it/ (accessed on 20 January 2020).

30. Guelpa, E.; Mutani, G.; Todeschi, V.; Verda, V. Reduction of CO_2 emissions in urban areas through optimal expansion of existing district heating networks. *J. Clean. Prod.* **2018**, *204*, 117–129. [CrossRef]

31. Technical Committee: ISO/TC 207/SC 5 Life Cycle Assessment. *Environmental Management–Life Cycle Assessment–Requirements and Guidelines, ISO 14040/44; 2006*; ISO: Geneva, Switzerland, 2006.

32. Ecoinvent. *Ecoinvent 3 Database*; Ecoinvent Center: Bern, Switzerland, 2013.

33. Noussan, M. Allocation factors in Combined Heat and Power systems–Comparison of different methods in real applications. *Energy Convers. Manag.* **2018**, *173*, 516–526. [CrossRef]

34. Ente Italiano di Normazione, Tubi di acciaio non legato adatti alla saldatura e alla filettatura-Condizioni tecniche di fornitura. Available online: http://store.uni.com (accessed on 3 March 2020).

35. Tranter-The Heat Transfer People. Tranter Website. Available online: https://www.tranter.com/ (accessed on 20 January 2020).

36. AlfaLaval. Alfa Laval Website. Available online: https://www.alfalaval.com/ (accessed on 20 January 2020).

37. Logstor. Logstor Website. Available online: https://www.logstor.com/ (accessed on 20 January 2020).

38. GreenDelta. OpenLCA Website. Available online: http://www.openlca.org/ (accessed on 20 January 2020).

39. Leiden University. *Leiden University Webpage*; Leiden University: Leiden, The Netherlands, 2020.

40. Hischier Roland, B.W.; Althaus, H.J.; Bauer, C.; Doka, G.; Dones, R.; Frischknecht, R.; Hellweg, S.; Humbert, S.; Jungbluth, N.; Köllner, T.; et al. *Implementation of Life Cycle Impact Assessment Methods*; Swiss Centre for Life Cycle Inventories: St. Gallen, Switzerland, 2007.

41. Guinée, J.B.; Lindeijer, E. (Eds.) *Handbook on Life Cycle Assessment-Operational Guide to the ISO Standards*; Springer: Berlin/Heidelberg, Germany, 2002. Available online: https://link.springer.com/article/10.1007/BF02978897 (accessed on 21 September 2020)

42. CML—Department of Industrial Ecology. *CML-IA Characterisation Factors*; Leiden University: Leiden, The Netherlands, 2016. Available online: https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors (accessed on 20 January 2020).

43. Acero, A.P.; Rodriguez, C.; Ciroth, A.; Rodríguez, C.; Ciroth, A. LCIA Methods-Impact Assessment Methods in Life Cycle Assessment And Their Impact Categories. Greendelta. Available online: https://www.openlca.org/ (accessed on 20 January 2020).

44. ESU Services. *Description of Life Cycle Impact Assessment Methods*; ESU-Services Ltd.: Uster, Switzerland, 2018.