Sustainable enhancement of district heating and cooling configurations by combining thermal energy storage and life cycle assessment

Silvia Guillén-Lambea [1,2], Monica Carvalho [3*], Monica Delgado[1,2], Ana Lazaro [2]

[1] University Center of Defense, Ctra. Huesca, s/n, 50090, Zaragoza, Spain.

[2] Aragón Institute for Engineering Research (I3A), Thermal Engineering and Energy Systems Group (GITSE), University of Zaragoza, Agustín Betancourt Building, C/María de Luna 3, 50018 Zaragoza, Spain

[3] Department of Renewable Energy Engineering, Federal University of Paraíba, Campus I. Cidade Universitária, s/n - Castelo Branco - João Pessoa - Paraíba - 58051-970, Brazil.

* Corresponding author: e–mail: monica@cear.ufpb.br

Silvia Guillén-Lambea ORCID: 0000-0003-3269-023X

Mónica Carvalho ORCID: 0000-0002-8524-3452

Mónica Delgado ORCID:0000-0002-8015-4469

Ana Lázaro ORCID: 0000-0001-7360-4188

ABSTRACT

District heating and cooling systems are designed and optimized to respond to the latest challenges of reducing energy demands while fulfilling comfort standards. Thermal energy storage (TES) with phase change materials (PCMs) can be employed to reduce the energy demands of buildings. This study considers a residential district located in Spain, where a general framework has been established to identify optimal combinations of energy conversion, delivery technologies, and operating rules. The life cycle assessment methodology was implemented within a mathematical model, and the objective function considered the minimization of environmental loads. Two environmental impact assessment methods were applied within the LCA methodology: IPCC 2013 GWP 100y and ReCiPe. Four optimal configurations were considered: a reference system (gas boiler, and split-type air conditioners) and then three TES-based systems: one sensible (STES, water) and two latent (LTES1 - paraffin emulsion, and LTES2 - sodium acetate trihydrate). Hourly environmental loads associated with electricity imports from the national grid were available. The conventional energy system

always presented the worst performance from an environmental viewpoint, being penalized by the high consumption of natural gas. Regarding carbon emissions, LTES1 showed the lowest emissions, followed by STES and LTES2 (reductions in energy demands compensated the impact of paraffin, and results of STES are strongly dependent on tank design). However, considering the ReCiPe method, STES presented the lowest loads, followed by LTES1 and LTES2 (overall impacts of LTES1 with paraffin are higher than STES with water, mainly due to the paraffin and the high volume required).

KEYWORDS

Life cycle assessment, Phase change materials, Thermal energy storage, District heating and cooling, Sustainable enhancement

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AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and methodology. Material preparation, data collection and life cycle assessment were performed by Silvia Guillén-Lambea and Monica Carvalho, thermal energy storage design and phase change material selection were performed by Mónica Delgado, and construction of the mathematical model and its calculations were performed by Ana Lázaro. The first draft of the manuscript was written by Silvia Guillén-Lambea, and edited and proofread by Monica Carvalho. Finally, all authors contributed to the final version of the manuscript.

1. INTRODUCTION

It is estimated that global energy demands will increase by 80 % by 2050, with consequent 50% more greenhouse gas (GHG) emissions primarily due to a 70% growth in energy-related CO_2 emissions (OECD and the PBL Netherlands Environmental Assessment Agency, 2012). Security in the supply of energy and reduced emissions can be achieved through improvement in energy efficiency, energy savings, a higher proportion of renewable energy, and process-wide integration.

District heating and cooling systems (DHC) distribute thermal energy to multiple buildings through a network of underground pipes, and the use of thermal energy storage (TES) can provide substantial benefits from economic, energy, and environmental viewpoints (Serra et al., 2009).

District air conditioning systems have been experiencing considerable advances lately, being optimized to respond to the latest challenges of reducing the energy demand of buildings while maintaining the thermal comfort level of residences. Phase change materials (PCMs), for example, can be employed to reduce the heating and cooling demands of buildings. A review of TES with PCMs, including heat transfer analysis and applications, was accomplished by (Zalba et al., 2003). TES using solid-liquid PCMs is a widespread technique because of the high thermal energy storage per unit volume. Currently, the utilization of two-phase materials such as paraffin dispersed in water, results in an effective latent heat storage medium (e.g., PCM emulsions, microencapsulated PCM slurries) (Delgado et al., 2012). Although the use of PCMs is nowadays scientifically developed, there are still environmental unknowns that are a strong motivation for further research.

A generalized environmental conscience has emerged, raising awareness and generating demands for products with enhanced sustainability (Carvalho et al., 2016). However, reductions in environmental impacts can only be achieved after adequate calculations. The life cycle assessment (LCA) is the leading methodology to measure product sustainability, which refers to the environmental negative impacts and benefits in decision-making processes towards more sustainable products throughout their life cycle. Once environmental impacts are quantified, actions can be carried out to reduce this burden.

Important environmental benefits were revealed by an LCA (Raluy et al., 2014) conducted on an energy system with solar thermal energy and seasonal TES using water as storage fluid for air conditioning of a district. PCMs for solar energy storage have been studied and considered efficient from an environmental aspect (López-Sabirón et al., 2014), with the preferred PCMs being paraffin, fatty acids, and salt hydrates (Kyriaki et al., 2017). Oró et al. (2012) carried out comparative LCAs for three TES systems for solar plants (solid media, molten salts, and PCM) and concluded that solid media were the most appropriate from an environmental viewpoint.

Considering the life cycle performance, PCMs are more environmentally friendly than their reference cases (Kylili and Fokaides, 2016). Gracia et al. (2015) added PCM to a Mediterranean building envelope, and verified a decrease in energy consumption during the operation stage, with an overall 10 % reduction in global impacts. Falco et al. (2017) introduced an innovative storage device, called ColdPeak, which demonstrated unique properties in terms of charging/discharging storage power. The environmental impacts associated with ColdPeak were extremely low due to the amount of energy saved thanks to its application. Cabeza et al. (2014) carried out an LCA of PCMs employed in buildings and obtained high levels of embedded energy within PCMs. It is therefore not straightforward to affirm that the (higher) impacts associated with manufacture are compensated by reductions in the operational impacts, which was also the conclusion of Miró et al. (2015). The "Speicher-LCA" project assessed the environmental performance of a variety of innovative materials available for energy storage in buildings, as presented by Horn et al. (2018). Nienborg et al. (2018) verified that PCM could be environmentally beneficial compared to water if used in an application with a small useful temperature difference (e.g., cooling). Adeoye et al. (2013) developed a comparative LCA of two thermal energy storage systems for a concentrated solar power plant, and verified that molten salt TES halves the environmental impacts in comparison with concrete TES. However, the quantification of environmental impacts in DHC systems remains underexplored (Bartolozzi et al., 2017), especially regarding latent heat storage.

A general framework has been established *a priori* (Pina et al., 2018a, 2018b) to identify optimal combinations of energy conversion and delivery technologies, as well as operating rules for the systems. The framework was utilized herein to optimize four scenarios of an energy system that meets the thermal energy demands (space heating, hot water, and cooling) of a residential district (500 units). The objective function considered was the minimization of environmental loads.

The environmental loads associated with four optimal district energy systems were calculated and compared: a conventional system constituted of a gas boiler and air conditioning units for each residential unit, and three TES-based DHC systems, constituted of reversible heat pumps, a photovoltaic solar field (PV panels), and thermal storage tanks (water, paraffin emulsion, and sodium acetate trihydrate).

The objective is to verify whether the environmental loads associated with the manufacturing and operation phases of a TES-based district air conditioning system are sufficiently low in comparison with the conventional system. Moreover, the study evaluates if the environmental impact of the latent heat storage system during its operation stage is sufficiently low to balance out the environmental impacts associated with the manufacturing phase of PCMs.

2. MATERIALS AND METHODS

2.1. DHC system

The energy systems considered herein were designed to meet the space heating, hot water, and cooling demands of a residential district located in Zaragoza, Spain (41°39'21" N 0°52'38" O). According to the Köppen-Geiger climate type map (Peel et al., 2007), the climate of Zaragoza is arid steppe hot (Climate Bsh), and the yearly sum of solar irradiation for optimally inclined photovoltaic modules is 1800 kWh/m^2 (Photovoltaic Geographical Information System, 2019). The residential area encompasses 500 residential units of 100 m^2, and energy demands have been established *a priori* (Raluy et al., 2014).

Table 1 Annual energy demands for the selected district

	Total demand	Peak demand
Space heating	2,397.5 MWh / 47.9 kWh/m^2	1,876.1 kW
Hot water	507.5 MWh / 10.1 kWh/m^2	
Cooling	973.2 MWh / 19.5 kWh/m^2	2,285.8 kW

The district energy systems were modeled in Lingo software version 11 (Lindo Systems, 2011), which provides a completely integrated package for the solution of optimization models. The solution of the optimization model yielded an energy system (configuration and operation) with minimum GHG emissions that meet the thermal energy demands of the district system.

The model was solved considering conventional equipment (gas boiler for heating and split-type air conditioners = “reference system”) and then considering less routinely deployed technologies: one sensible thermal energy system = “STES”, and two latent thermal energy systems = “LTES1” and “LTES2”.

The optimization model compares all combinations of energy conversion and delivery technologies, on an hourly basis, to establish the optimal solution, which encompasses the equipment to be installed and its operation throughout the year. Gas boilers, heat pumps, and energy storage are available to satisfy the heating demands, while electricity can be supplied by the electric grid or by the photovoltaic (PV) panels. The physical models are based on real operation performance data provided by manufacturers: the efficiency of the gas boilers (η_{boiler}) is 0.9, and the coefficient of performance (COP) and heating capacity of the heat pumps vary with the outlet temperature of the condenser. The energy efficiency ratio (EER) and the cooling capacity vary with the evaporator's outlet temperature. For the PV panels, the nominal power of each panel (P_{max}) is 245 W, and the efficiency (η_{panel}) is 16.1 %.

Table 2 shows the equipment selected for each configuration. The technical specifications for the gas boiler, reversible heat pump, air conditioning units, and PV panels were obtained in consultation with manufacturers. Auxiliary equipment, such as pumps and pipes, were not included in the study because they are common to all configurations.

Table 2 Equipment selected for the different configurations.

<table>
<tr><th>System</th><th>Heating equipment</th><th>Cooling equipment</th><th>Auxiliary equipment</th><th>Storage tank</th><th>Thermal storage medium</th></tr>
<tr><td>Reference</td><td>Gas boiler 2,360 kW</td><td>500 split-type a/c, 4.75 kW each</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>STES</td><td rowspan="3">Reversible heat pump: 1,766 kW</td><td rowspan="3">Reversible heat pump: 1,365 kW</td><td rowspan="3">Solar field: PV panels 3,200 m²</td><td>Cylindrical, reinforced concrete 118.6 m³</td><td>Water at 30 ºC to 65 ºC</td></tr>
<tr><td>LTES1</td><td>Cylindrical insulated stainless steel 145.0 m³ Mixers 37.7 kW</td><td>Paraffin at 30 ºC to 50 ºC</td></tr>
<tr><td>LTES2</td><td>Stainless steel modules 83.5 m³</td><td>SAT at 30 ºC to 58 ºC</td></tr>
</table>

The two different PCMs were selected following the possible operation temperature ranges of the heat pump, and because there is sufficient published data on their thermophysical properties and storage systems. The emulsified PCM employed in LTES1 is a low cost paraffin, more specifically a by-product of the petroleum refining process (Delgado et al., 2012). The solids content of this PCM emulsion is approximately 60 %, with an average particle size of 1 µm. Within its melting temperature range (30 ºC to 50 ºC), the paraffin emulsion can store 122 MJ/m^3; it must be highlighted that the phase change temperature range is quite extensive, as the PCM is a by-product and has not undergone purification processes (Delgado et al., 2012). Regarding LTES2, the issue of phase separation was taken into account and therefore SAT with Carboxy-Methyl-Cellulose (CMC) as a thickening agent was considered (mass fraction 1%) (Kong et al., 2019). SAT has a melting point of 58 ºC, relatively high melting enthalpy at 264 kJ/kg (Dannemand et al., 2015), and within its operation temperature, density is between 1.25 kg/m^3 and 1.45 kg/m^3 (Dannemand et al., 2018). Also, SAT presents stable supercooling, and therefore generally reliable mechanisms are required for the controlled initialization of crystallization (Englmair et al., 2018a).

The solution of the optimization model provided the storage capacity, which must be 4,820 kWh (working at both temperature levels, 60 ºC and 65 ºC). The water storage tank was designed following (Raluy et al., 2014).

For the design of the paraffin storage tank, geometric similarity has been applied based on a 46 L storage tank successfully tested previously (Delgado et al., 2017), resulting in 29 stainless steel tanks (5 m^3 each). A mixer was installed at the upper part of the central axis to improve storage efficiency and promote heat transfer. Herein mixers were sized following geometric similarity and the similarity of Reynolds number. The mixer installed in each storage tank operates at 171 rpm (mechanical power 1.3 kW). Considering efficiency and friction losses, a 3.0 kW motor was selected.

For the design of the SAT storage tank, the segmented heat-storage prototype proposed by Englmair et al. (2018b) was adopted due to the availability of technical specifications. The segmented PCM heat storage is constituted of flat units, which enclose the SAT with CMC. Parallel flow channel heat exchangers are attached on the top and bottom of each flat PCM container. As aforementioned, crystallization triggering is required, which is accomplished utilizing an activation device mounted on a flange of the air expansion chamber of each PCM unit. Using this device, solid SAT crystals are added to the supercooled SAT. Each PCM unit also counts with an expansion vessel. According to the phase change enthalpy of SAT with CMC, considering its density and assuming a 100 % storage efficiency, 446 PCM units are required to meet the storage capacity requirements (4,820 kWh).

Electricity could be imported from the electric grid, and its hourly GHG emissions were also available, indicating the temporal nature of the emissions.

2.2. Life cycle assessment

Life Cycle Assessment (LCA) is a validated and consolidated methodology for the quantification of environmental impacts throughout the life cycle of a product, process or activity (Guinée et al., 2001). LCA has been standardized by the International Organization for Standardization (ISO) (2006a, 2006b), and presents four interrelated steps: i) Definition of goal and scope (identification of the object to be analyzed, establish context and system boundaries); ii) Analysis of inventory (identification and quantification of material and energy flows as inputs as well as environmental releases as outputs); iii) Impact assessment (application of an environmental assessment method), and iv) Interpretation (analysis of results, comparison of alternatives). An excellent introduction to LCA can be consulted in (Guinée et al., 2011).

i) Definition of goal and scope

The aim of this study is to quantify and compare the environmental loads associated with the four district energy systems defined in the previous section. The results will determine if the environmental loads associated with the manufacturing and operation phase of a district air conditioning system, including TES, are sufficiently low in comparison with a more conventional system. Additionally, the evaluation of the environmental impact of the two latent heat storage systems will evaluate if the emissions associated with the operation stage are satisfactorily low to balance out the emissions related to manufacturing the PCMs.

The functional unit considered herein was the energy required to meet the energy demands of the residential district.

ii) Analysis of inventory

The life cycle inventory (LCI) considers the material composition of the equipment and includes extraction and processing of raw materials, manufacturing, transportation and distribution, use, maintenance, and final disposal. This step focused on the material composition of the equipment for the four energy systems and did not include distribution networks, which are similar across systems. Maintenance, dismantling, recycling, and disposal of equipment have not been included in this research.

Table 3 presents the main material composition for the equipment, while Table 4 shows the main material composition per system configuration. PV refers to photovoltaic, and ST refers to storage tank.

Table 3 Main material composition per equipment

Materials (kg)	Gas Boiler	Splits	Heat pump	PV panels	ST Water	ST Paraffin	ST SAT
Stainless steel	589.9	4,174.5	13,154.2	-	1,738.6	19,263.9	297,963.0
Reinforcing steel	-	-	-	-	43,478.3	-	-
Steel, low-alloyed	11,443.4	8,349.0	3,507.9	699.9	-	-	-
Concrete	-	-	-	-	120,371.4	-	-
Copper	589.9	4,950.0	3,858.6	822.0	-	-	-
Aluminium	353.9	2,475.0	-	68.7	-	-	-
Brazing solder	141.6	-	-	-	-	-	-
Electronic component	-	275.0	-	-	-	-	-
Lubricating oil	-	-	298.2	-	-	-	-
Polyethylene	30.0	4,950.0	-	200.5	-	-	-
Polystyrene	-	-	-	-	5,576.7	-	-
Polyurethane	-	-	-	-	-	386.6	8,405.3
Polyvinylchloride	-	-	175.4	29.7	297.3	-	449.0
Refrigerant R134a	-	-	542.0	-	-	-	-
R410	-	1,650.0	-	-	-	-	-
Tube insulation (elastomere)	-	-	1,753.9	-	-	-	-
Alkyd paint	59.0	-	-	-	-	-	-

Table 4 Main material composition by system configuration

	Reference		STES		LTES1		LTES2	
Materials	(kg)	%	(kg)	%	(kg)	%	(kg)	%
Stainless steel	4,764.4	11.9%	14,892.8	7.6%	32,418.1	72.4%	311,117.2	93.2%
Reinforcing steel	-	-	43,478.3	22.1%	-	-	-	-
Steel, low-alloyed	19,792.4	49.4%	4,207.8	2.1%	4,207.8	9.4%	4,207.8	1.3%
Concrete	-	-	120,371.4	61.2%	-	-	-	-
Copper	5,539.9	13.8%	4,680.6	2.4%	4,680.6	10.5%	4,680.6	1.4%
Aluminium	2,828.9	7.1%	68.7	0.0%	68.7	0.2%	68.7	0.0%
Brazing solder	141.6	0.4%	-	-	-	-	-	-
Electronic component	275.0	0.7%	-	-	-	-	-	-
Lubricating oil	-	-	298.2	0.2%	298.2	0.7%	298.2	0.1%
Polyethylene	4,980.0	12.4%	200.5	0.1%	200.5	0.4%	200.5	0.1%
Polystyrene	-	-	5,576.7	2.8%	-	-	-	-
Polyurethane	-	-	-	-	386.6	0.9%	8,405.3	2.5%
Polyvinylchloride	-	-	502.3	0.3%	205.1	0.5%	654.1	0.2%
Refrigerant R134a	-	-	542.0	0.3%	542.0	1.2%	542.0	0.2%
R410	1,650.0	4.1%	-	-	-	-	-	-
Tube insulation (elastomere)	-	-	1,753.9	0.9%	1,753.9	3.9%	1,753.9	0.5%
Alkyd paint	59.0	0.1%	-	-	-	-	1,753.9	0.5%

iii) Impact assessment

The LCA was carried out with SimaPro software v.9.0.0.35 (PRe Consultants, 2018), utilizing the Ecoinvent database (“Ecoinvent,” 2018), and two environmental impact assessment methods: IPCC 2013 GWP 100y (“Intergovernmental Panel on Climate Change - IPCC, 2013) and the ReCiPe 2016 method (Huijbregts et al., 2016). The IPCC method converts atmospheric emissions into a common metric (CO_2-eq) using the conversion factors published in the reports of the IPCC, based on the Global Warming Potential (GWP) of the emissions contemplated, throughout a horizon of 100 years. The ReCiPe method (Endpoint (H) V1.13) was included to broaden environmental considerations in the impact assessment, incorporating relevant environmental burdens into different impact categories that allow the evaluation of damages to human health, ecosystem quality, and resources.

SimaPro was employed to calculate the environmental impacts associated with the different configurations, except for electricity consumption. One of the innovations presented herein is the utilization of hourly environmental data associated with the electricity mix provided by the Spanish grid, which was obtained from the solution of the optimization model. Figure 1 depicts the calculations steps for the proposed methodology.

Fig. 1 Methodology scheme.

The fourth LCA step, iv) Interpretation (analysis of results), is presented in Section 3.

3. RESULTS AND DISCUSSION

The annual energy consumptions associated with each configuration, during its operational stage, were obtained from the solution of the optimization model. Table 5 shows the results.

Table 5 Energy flows associated with each energy system (annual values)

	Reference	STES	LTES1	LTES2
Electricity imported from the grid (kWh)	51,170	746,886	656,780	637,215
Natural gas (Nm^3)	350,207	-	-	0

Electricity produced by PV panels (kWh)	-	607,618	601,727	601,727
Electricity consumption of the TES agitation system (kWh)	-	-	19,565	0
Electricity consumption of heat pumps (kWh)	-	1,220,983	1,048,064	1,048,064
Electricity consumption of pumps (kWh)	-	133,520	190,878	190,878

The total electricity consumption of the latent thermal energy storage systems is slightly lower than the sensible thermal energy storage system. In the case of paraffin, the reduction is 7.1 %, with an 8.5 % reduction for SAT. The electricity imported from the grid is reduced by 12.1 % for the paraffin and by 14.7 % for SAT, when compared with STES.

The first environmental analysis was developed regarding carbon emissions. Once data were implemented within SimaPro, the IPCC 2013 GWP 100y method was selected, and results for the carbon emissions associated with each configuration were obtained. Hourly electricity emissions regarding consumption from the national electric grid were obtained from the optimization procedure. These are summarized in Table 6. The absolute emissions associated with the construction phase were divided by the corresponding lifetimes to obtain annual emissions.

The expected lifetimes considered were: storage tanks 50 years, split-type a/c units 10 years, remaining equipment 20 years. It was assumed that refrigerant R410A within each a/c unit is replaced every five years. The expected lifetime for paraffin and SAT is 20 years[1].

Table 6 Annual carbon emissions associated with each energy configuration (kg CO_2-eq/year)

Carbon emissions (kg CO_2-eq/year)		Reference	STES	LTES1	LTES2
Construction	Gas boiler	6,240	-	-	-
	Splits	71,020	-	-	-
	Heat pumps	-	13,950	13,950	13,950
	Photovoltaics	-	4,950	4,950	4,950
	Storage tanks	-	3,580	2,040	31,660
	PCM	-	-	3,180	5,610

[1] As these PCMs are still under development, there are no data available concerning the expected lifetime, no standard method to test ageing over time, and durability remains unknown.

Operation	Electricity	19,000	144,178	123,433	123,433
	Electricity TES agitation system	-	-	3,971	-
	Natural gas	1,110,000	-	-	-
Total		1,206,260	166,658	151,524	179,603

The carbon emissions emitted by the equipment of the conventional system are almost four times higher than the TES-based systems. This is mainly due to the single air conditioning units (45,900 kg CO_2-eq/year) and the refrigerant R410A (25,120 kg CO_2-eq/year). Also, the high emissions associated with the consumption of natural gas demonstrate that conventional district systems are not a solution to be taken into account for present and future cities, at least not from the perspective of carbon emissions.

The result obtained for LTES1 with the paraffin emulsion reveals that this configuration is the most environmentally-friendly option, with a reduction of 10% in carbon emissions in comparison with STES.

The expected lifetime for paraffin was considered 20 years, which is probably a very optimistic value. However, the results show that the impact of PCMs is not as high as expected, and therefore a change of material every five or ten years will only slightly alter the results obtained. When the lifetime of paraffin is four years, the emissions of STES and LTES1 are similar. However, if the lifetime of paraffin is higher than four years, the emissions associated with LTES1 are lower.

Moreover, the results show that for the reference system, 94 % of carbon emissions are produced during the operation phase. When considering thermal energy storage, the percentage of carbon emissions due to the construction phase is much more relevant. Research efforts made to date have succeeded in reducing the operational energy consumption of district thermal systems and, consequently, the associated carbon emissions.

For the less routinely deployed systems analyzed (STES, LTES1, and LTES2), the carbon emissions produced during the construction phase correspond to 13 %, 16 %, and 31 % of the overall environmental impacts, respectively. These values reflect a pressing need to focus investigation works on the environmental impacts associated with the construction of equipment, as these begin to be relevant in the overall life cycle of thermal systems.

The second environmental analysis employed the ReCiPe method. Human health, ecosystems, and resources damage indicators were calculated for the construction phase, and Figure 2 depicts the results obtained for each system configuration.

Fig. 2 Damage indicators for construction of each system configuration (ReCiPe method, endpoint H)

The damage indicators of the reference system are much higher than those of the sensible thermal storage system, and human health is the indicator that causes a pronounced difference. The LTES2 system with SAT obtained very unfavorable indicators compared to the other two storage systems. Further investigation of these poor results of LTES2 leads to Table 7, which shows a breakdown of the environmental loads associated with each piece of equipment, storage tank, and PCMs, for the three thermal storage systems. Water (storage fluid) does not appear because its loads are negligible.

The damage indicators obtained for the common equipment are important (2.56 kPt), of which 1.91 kPt are due to the heat pump and 0.65 kPt due to the photovoltaic system. The SAT thermal storage tank obtained high damage indicators (5.35 kPt), demonstrating the need to invest efforts towards the design and optimization of new district thermal equipment from environmental viewpoints. The paraffin storage tank presents similar damage indicators to the water tank (0.37 *vs.* 0.39), although its volume is 22 % higher. The paraffin obtains slightly worse indicators than SAT, although 74 % more paraffin is required for the same thermal storage capacity.

Table 7 Damage indicators for equipment, tanks, and PCM (ReCiPe method, endpoint H)

Category	Human Health	Ecosystems	Resources	Total
Units	(kPt)	(kPt)	(kPt)	(kPt)
Heat pump + PV panels	1.40	0.40	0.76	2.56
Storage tank: water	0.14	0.06	0.14	0.33
Storage tank: paraffin	0.12	0.04	0.21	0.37
Storage tank: SAT	1.72	0.56	3.06	5.35
Paraffin	0.14	0.06	0.55	0.75
SAT	0.25	0.11	0.30	0.66

The volume of PCM required for the storage of thermal energy affects not only the PCM indicators but also those related to the storage tank. Therefore, it is interesting to analyze the damage indicators associated with the three systems per unit of volume (m^3) of PCM / water. These values are shown in Table 8.

Table 8 Damage indicators associated per volume unit of PCM/water (annual values)

Category	Volume	Total	Human Health	Ecosystems	Resources
Units	(m^3)	(kPt/ m^3)	(kPt/ m^3)	(kPt/ m^3)	(kPt/ m^3)
Water storage tank	118.60	3.29	1.37	0.57	1.35
Water	118.60	3.5e-03	1.7e-03	0.7e-03	1.1e-0.3
Paraffin storage tank	145.00	2.57	0.84	0.28	1.45
Paraffin	145.00	5.18	0.96	0.43	3.80
SAT storage tank	83.50	64.03	20.64	6.76	36.63
SAT	83.50	7.90	2.98	1.36	3.56

The results show that SAT presents higher damage indicators than paraffin; moreover, the SAT storage tank also has considerable values associated with the damage indicators per unit of volume. It is concluded that the volume of PCM is a critical parameter that should be optimized to minimize the environmental impacts associated with thermal energy storage.

The effects of climate change have not been taken into account neither in the configuration or in the operation of the energy systems proposed herein. This will be the focus of future work by the authors. Due to climate change, heating demands are expected to decrease while cooling demand should increase because of higher external temperatures but also due to more intense solar gains throughout the near future years. Rey-Hernández et al. (2018) estimated the air ambient temperatures for 2020, 2050, and 2080 for Valladolid (Spain), which presents a similar climate to Zaragoza. External air temperature is expected to increase by 1.5 °C in winter and by 3.0 ºC in summer, between 2020 and 2050. The meteorological data reported lead to a decrease of 12% in heating demands while cooling demands increase by 16 % between 2020 and 2050 (Rey-Hernández et al., 2018).

Herein any estimated variations in energy consumption are expected to be fully covered by the proposed systems until 2050. However, cooling energy consumption after 2050 should be studied explicitly at a later stage. Climate change is an essential factor, which should be included in further research to propose new improvements in the sustainability of future cooling systems but also to reduce the cooling load in warm climates. An initial approach to the study of climatic characterization and future trends was carried out by (Abrahao et al., 2017), who verified that maximum temperature presented steep annual increments ($p<0.001$, 0.07°C/year). Although (Abrahao et al., 2017) focused on the production of electricity from solar and wind resources, climatic characterization and trends are very helpful to establish dynamic energy demands (Silva et al., 2019; Eterna et al., 2018; Silva et al., 2018; Medeiros et al., 2019).

The configurations of the proposed energy systems were obtained from the solution of an optimization model, focused on the minimization of environmental loads. As a next step, the life cycle cost analysis of the less routinely deployed technologies should be carried out and compared with a configuration based on conventional equipment, to verify the economic viability of PCM systems.

The study presented herein is a starting point to build upon, and further research should focus on LCA for latent heat storage in thermal systems applications, more precisely in district heating and cooling systems. The reduction of energy demands in the operation phase (consequent reduction of environmental impact) means that the environmental impact associated with the manufacturing phase acquires much more relevance. The research presented herein identifies and stresses urgency regarding the inclusion of LCA criteria in the design of industrial equipment.

This study contributes by outlining the priorities of investigation, development, and demonstration of new concepts and technologies to enhance sustainability and reduce the final consumption of primary energy, considering the life cycle holistically. These priorities include the integration of strategies and technologies to increase energy efficiency, the use of renewable energy and storage, development of new technologies, and demand management systems. Better use of energy resources will result in the protection of local jobs. Furthermore, a decrease in the use of available energy results in a minimization of environmental impacts, which is a benefit to all citizens.

4. CONCLUSIONS

This study quantified and compared the environmental loads associated with four optimal energy systems: a conventional system constituted of a gas boiler and air conditioning units for each dwelling, and three TES-based DHC systems, constituted of reversible heat pumps, a thermal storage tank (sensible: with water, and latent, with PCMs: paraffin and SAT) and a photovoltaic solar field. These systems were optimized considering the energy demands of a residential district located in Zaragoza (Spain), with 500 dwellings (100m^2 each).

Two environmental impact assessment methods were applied within the LCA methodology: IPCC 2013 GWP 100y and ReCiPe, which provided a more global perspective. It was verified that a traditional energy system, although optimized, presented the worst performance from both environmental viewpoints. The traditional, coventional configuration was penalized by the high consumption of natural gas.

Much lower environmental impacts were obtained when energy integration strategies were employed. The TES-based systems presented 86 %, 87 %, and 85 % lower carbon emissions, for the STES with water and LTES1 and LTES2, respectively, in comparison with the traditional system. Regarding the ReCiPe method, the volume of PCM was identified as a crucial parameter and, therefore, it should be optimized from the early stages of the design of new thermal energy storage systems.

The carbon emissions associated with LTES1 were lower than STES, because the impact of paraffin production was compensated by reductions in energy demands during the operational phase of the DHC system. This is valid when the lifetime of paraffin is higher than four years.

The results of the SAT system were strongly affected by the design of the tank, which relied on steel. It must be highlighted that information was obtained from a prototype due to the lack of commercially available data. Therefore it is vital to motivate and encourage the use of methodologies such as LCA in the early design stages of new equipment. More specifically, efforts could be directed to equipment within new optimized systems for thermal energy generation in districts.

When evaluating the LCIA damage indicators, the results confirm than the selected design of the SAT tank is out of range in comparison with paraffin. The overall impacts of LTES1 with paraffin are higher than STES with water, mainly due to the paraffin itself (both storage tanks present similar damage indicators) because of the considerable volume of paraffin required. Further research and additional efforts should be made towards the development and the improvement of PCMs to decrease the environmental impacts associated with the manufacturing phase.

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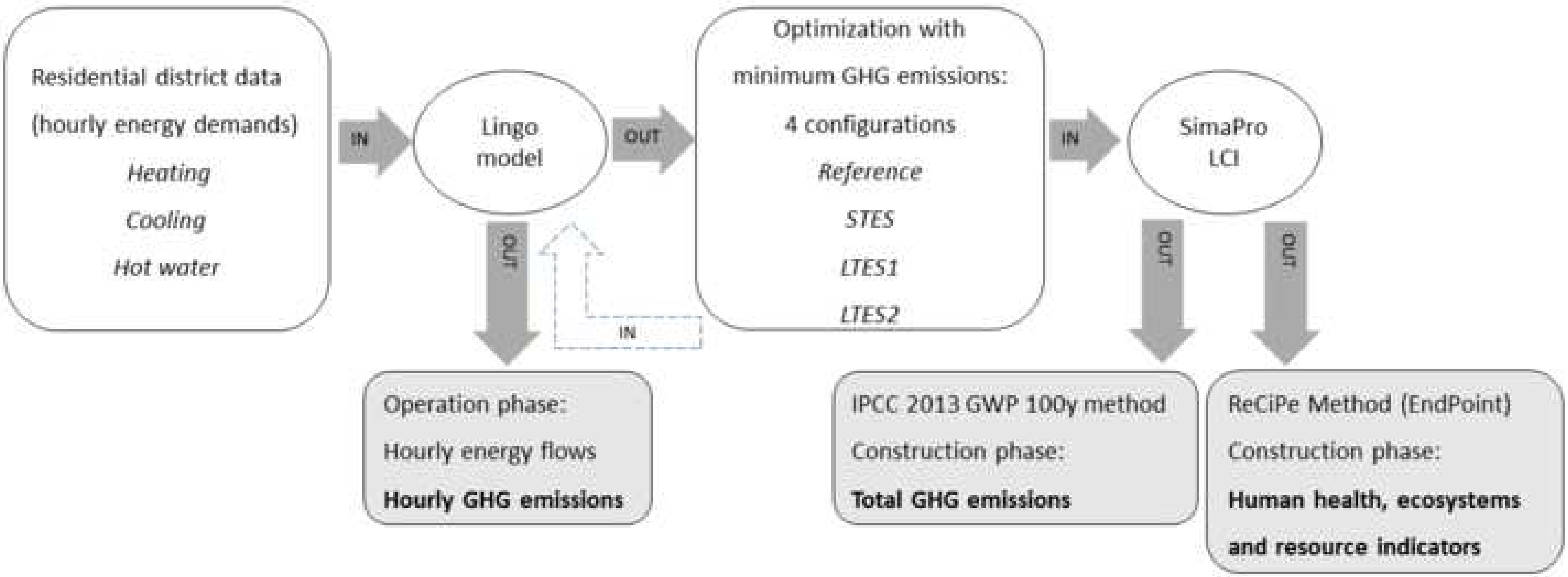
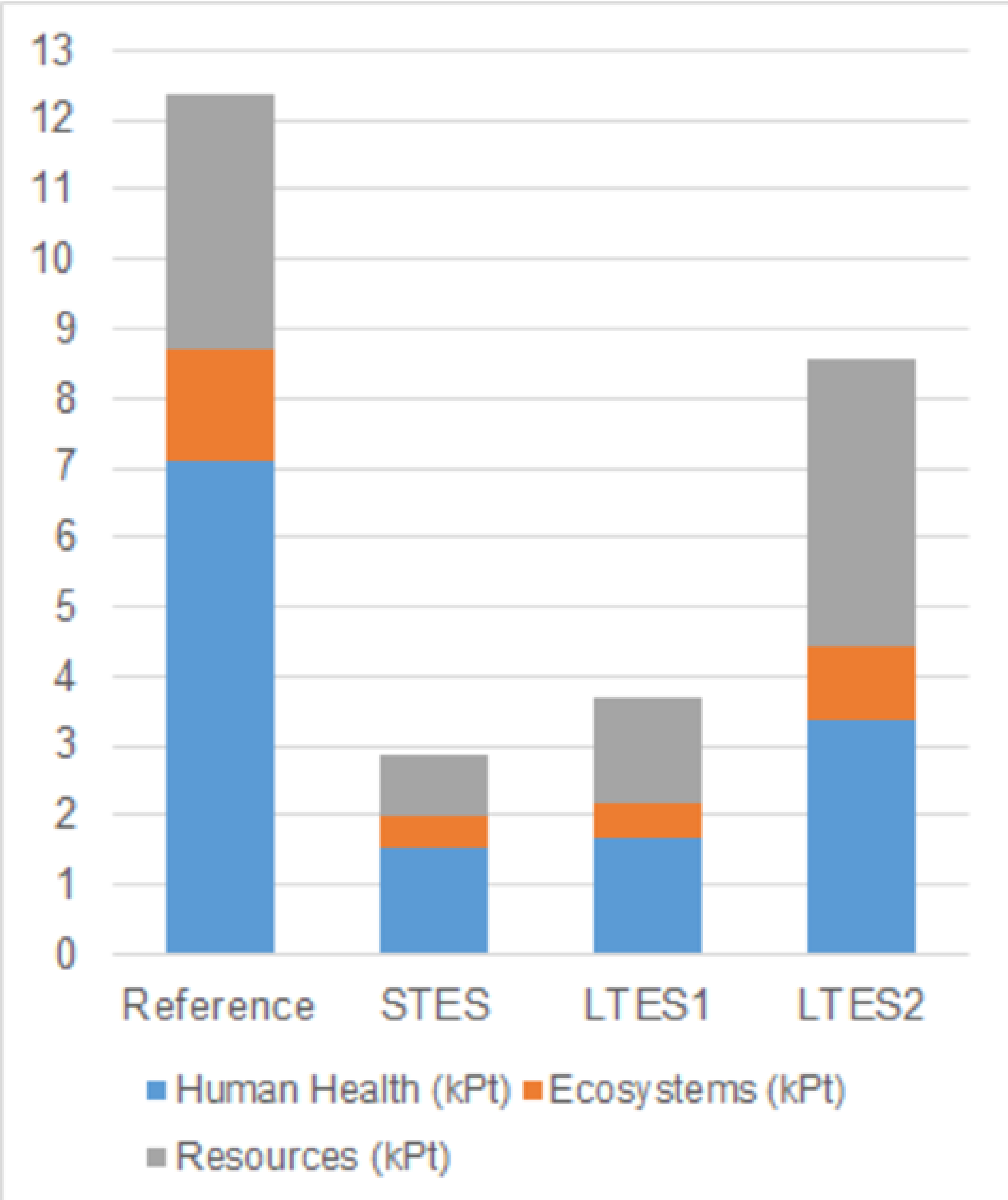
Figure 1



Residential district data
(hourly energy demands)
Heating
Cooling
Hot water
IN
Lingo model
OUT
Optimization with minimum GHG emissions:
4 configurations
Reference
STES
LTES1
LTES2
IN
SimaPro LCI
OUT
IN
Operation phase:
Hourly energy flows
Hourly GHG emissions
OUT
OUT
IPCC 2013 GWP 100y method
Construction phase:
Total GHG emissions
ReCiPe Method (EndPoint)
Construction phase:
Human health, ecosystems and resource indicators

Figure 2


13
12
11
10
9
8
7
6
5
4
3
2
1
0
Reference
STES
LTES1
LTES2
Human Health (kPt)
Ecosystems (kPt)
Resources (kPt)

Highlights

Four optimal energy systems are compared from environmental viewpoints via LCA

Conventional energy system is penalized by the high consumption of natural gas

Latent TES with paraffin presented lowest carbon emissions

With ReCiPe method, sensible TES with water presented the lowest burden

Graphical Abstract