Potential for Integration of a Renewable Combined Heating and Cooling System in Food Industries requiring Heat and Cold

Marc Medrano[1], Andrea Salandin[2], Cristian Solé[1], Ingrid Martorell[1], Roger Vilà[1] and Albert Castell[1]

[1] Sustainable Energy, Machinery and Buildings (SEMB) Research Group, INSPIRES Research Centre, Universitat de Lleida, Lleida (Spain)

[2] TF Centro de Tecnologías Físicas, Universitat Politècnica de València, Valencia (Spain).

Abstract

Night radiative cooling can be combined with solar thermal collection in one single device to produce heat during the day and cold during the night. This device is called RCE (Radiant Collector and Emitter) and could be integrated in processes requiring simultaneous heating and cooling demands, such as the food industry, to save non-renewable primary energy and operating costs. In this paper the temperature levels and amounts of heat and cold of seven food industries are analyzed and compared with the combined heat and cold production of the RCE for three different climates in Spain to assess its potential of integration. Two different sizing of the RCE field are presented, one tracking the heat demand, and the other tracking the cold demand. Results show the natural gas and electricity energy and cost savings associated to the partial replacement of the natural gas boiler (for heating loads) and the efficiency improvement of the electrically-driven chiller (for cooling loads) by the RCE. The best match is found with the juice canning industry, with primary energy savings of 62% in heat track and 81% in cold track.

Keywords: renewable heating and cooling, food industry, radiative cooling, solar thermal collection, simultaneous heating and cooling, primary energy savings

1. Introduction

Radiative cooling (RC) is a relatively old technology, already studied in the 70s (Vall and Castell, 2017), which is recovering interest lately due to the advent of selective surfaces with nanomaterials (Raman et al., 2014). It takes advantage of the low “effective” temperature of the sky during the night to dissipate heat by radiation, thus producing cold. This “effective” temperature is influenced by the behaviour of the atmosphere known as “infrared window”, which allows the pass of radiation at a certain wavelength (7-14 µm). Heat dissipation is produced by longwave radiation (thermal radiation) from a surface to the sky. The sky temperature during the night allows suitable cooling as temperatures can be lower than 0ºC or even -10ºC (Bell et al., 1960), During the day the solar radiation (shortwave radiation) is higher and the radiation balance results in thermal gains (heating). To produce cold a high emissivity radiative surface is needed and connected to different pipes where a fluid is circulating. The radiative surface emits energy as thermal radiation to the sky, cooling down the fluid by using a cover material transparent to thermal radiation.

Furthermore, this technology can be coupled with a flat plate solar thermal collector (Vall et al., 2020), creating a new device, the Radiative Cooler and Emitter (RCE), capable of producing in a renewable way hot water and cold (to support the cooling system), reducing the non-renewable energy consumption during the whole year, as well as the maximum installed power of the conventional production systems. Nowadays solar collectors are a well stablished technology, where research focuses on the use of selective surfaces (Suman et al., 2015; Valleti et al., 2014), nano-fluids (Suman et al., 2015; Verma and Tiwari, 2015) and concentration systems (Colangelo et al., 2015), but the radiative cooling technology shows a reduced development due to the lack of suitable materials and solutions in order to reduce the heat gains and the low energy density available (between 20-80 W/m2 (Cavelius, R. et al., 2005)). The most used solar thermal collectors in Europe are the flat plate solar collectors (mostly used for domestic hot water (DHW) production).

Little research has been done in the combination of both solar collection and radiative cooling in a single device

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(Erell and Etzion, 2000, 1996), but conventional covers are not suitable for radiative cooling. In this paper, a suitable adaptive cover, capable to adapt its optical properties to allow either thermal radiation to pass through (for radiative cooling) or block thermal radiation (for solar collection) is implemented in the new RCE device, as explained in (Vall et al., 2020). More recently, significant developments have been achieved in the field of materials capable to produce radiative cooling during both night and daytime. In 2013 at Stanford University, Rephaeli et al. were the first ones to develop such a material (Raman et al., 2014; Rephaeli et al., 2013). In 2015, Hu et al. (Hu et al., 2015) developed a spectral selectivity surface suitable for both solar collection and radiative cooling. The new surface, the TPET presents high absorptivity/emissivity in both the solar radiation and atmospheric window bands. However, Hu et al. did not consider the radiative properties of the cover of the solar collector/radiative cooler, using polyethylene as cover, which will reduce the efficiency during solar collection mode due to the high emissivity in the near-infrared wavelength (Hu et al., 2016).

The potential of the integration of the RCE novel device into different types of buildings in different climates has been studied elsewhere (Vall et al., 2018).

Solar collectors have been already integrated in many industrial processes in the last years. Over 800 solar thermal plants and more than 1 million m^2 of solar heat have been reported (Weiss and Spörk-Dür, 2019), many of them in the food industry. Several of these examples of solar collectors integration in industry are investigated in academic papers, such as the combination of solar collectors with heat pumps (HP) in canned fish factories (Quijera et al., 2014); the integration of solar collectors in heat recovery loops of dairy processes (Walmsley et al., 2015); the integration of a concentrating solar thermal plant in a textile factory (Carnevale, 2011); or the large scale solar plants use in copper recuperation processes (Cuevas et al., 2015). The food industry happens to demand both heating and cooling simultaneously. Seven examples of food processes which have been reported to demand both cooling and heating are beer brewing, food pasteurization, fluid milk processing, cheese processing, vegetable and fruit canning, juice canning, and poultry slaughtering (Liu et al., 2016). However, there is no study exploring the industry use of the combined renewable production of heat and cold using RCE devices.

In this paper the potential for integrating the above mentioned RCE technology in the food industry is studied in a monthly and annual basis. Primary energy and cost savings are reported and discussed for the seven industries and for three different climates in Spain.

2. Methodology

First of all, seven food industries (beer brewing, food pasteurization, milk processing, cheese processing, vegetal and fruits canning, juice canning and poultry slaughtering) are analyzed based on the annual loads for heating (hot and warm water) and cooling as well as shown in Table 1 (Liu et al., 2016). The second column, “HP Condenser Cooling needs” refers to the heat that needs to be dissipated in the condenser of the refrigeration heat pump, for the cooling needs of the industry, and assuming a COP of 3. Furthermore, characteristic ratios of heating loads over cooling loads for each industry are identified and can be compared with the RCE ratio of heating over cooling annual production. As the RCE is based on flat plate solar collectors for heating production, and this technology is limited to maximum water temperatures up to 70-80 ºC, two industry heating levels are distinguished: industry heating needs over 72 ºC, which are not suitable to be covered by the RCE, and heating needs below 72 ºC, compatible with RCE temperature levels. Thus, only the primary energy associated to these warm heat demands, normally in the form of hot water, is susceptible to be saved with the RCE integration. As Food pasteurization industry has no warm water needs as shown on Table 1, it will be not included in our analysis. It is observed that poultry slaughtering (with 2881 kJ/kg cold needs and 1800 kJ/kg heat needs) and cheese processing (1343 kJ/kg for cold and 1354 kJ/kg for heat) are the two most energy intensive processes.

Tab. 1: Heating and Cooling needs per kg of product for various food industries (adapted from Liu et al., 2016).

Industry process	Cooling needs (kJ/kg)	HP Condenser Cooling needs for COP=3 (kJ/kg)	Hot water needs (over 72 °C , kJ/kg)	Warm water needs (below 72 °C, kJ/kg)	Ratio total Heating/Cooling industry, η_{tot}	Ratio Warm Water /Cooling industry, η_{warm}	Ratio Warm Water /Condenser Cooling industry, $\eta_{warm,cond}$
Beer brewing	320	426.7	370	370	2.3	1.2	0.9
Food pasteurization	213.8	285.1	213.8	0	1.0	0.0	0.0
Milk	904.8	1206.4	141.2	141.2	0.3	0.2	0.1
Cheese processing	1343	1790.7	677	677	1.0	0.5	0.4
Vegetable and fruits canning	97.4	129.9	302	302	6.2	3.1	2.3
Juice canning	48.7	64.9	503.4	503.4	20.7	10.3	7.8
Poultry slaughtering	2881	3841.3	900	900	0.6	0.3	0.2

Second, the monthly and annual production of heat and cold per unit area of RCE can be calculated considering an average daily profile of heat and cold production, based on hourly values of meteorological data, taken from a METEONORM typical meteorological year (TMY) weather files. The heat production is calculated based on the average daily profile of horizontal solar radiation for each month and an average annual value for the efficiency of the RCE in solar thermal collector mode (60%). The cold production is determined based on the net night radiative sky cooling potential (Li et al., 2019) and an average annual RC efficiency (40%) based on recent RCE experimental data (Vall et al., 2020) . Three different big and representative cities in Spain with an important food industry activity, namely Seville, Barcelona and Bilbao, are selected for the study. Seville, located in the South, has high solar radiation and high cooling potential, Barcelona, on the Mediterranean See, has intermediate values, and Bilbao, located in the North, has a climate with low solar radiation and low cooling potential. Seville's climate is considered Mediterranean Continental, Barcelona's is Mediterranean Litoral, and Bilbao's Oceanic Litoral. Seville and Barcelona have the same Csa classification (Hot-summer Mediterranean climate) in the Köppen-Geiger climate system, and Bilbao has the Cfb classification (Oceanic climate).

It is important to note here that the RCE is only able to generate cold down to temperatures slightly below ambient (2-8 ºC below ambient temperature). As the cooling temperature levels for the food industry is generally in the range 0-15ºC (Liu et al., 2016), the cold generated by the RCE cannot replace directly the cooling needs. Instead, it will be used indirectly for the condenser cooling needs of the electrically driven refrigeration heat pump used in the industry to produce the cold-water service. Table 1 includes two columns with this information: the total HP condenser cooling needs (assuming a COP=3) and the ratio of warm water needs over condenser cooling needs, $\eta_{warm,cond}$. This is actually the more adequate industry ratio to compare with the ratio of heating over cooling production of the RCE. It is assumed that the condenser temperature with the RCE will be 5 ºC lower than the base case operation, thanks to the RCE night radiative cooling. This 5 ºC reduction of the condenser temperature will imply a 25% increase in the cooling COP (about 5 % improvement per 1 ºC reduction in the evaporator-condenser temperature lift). Note as well that a full coverage of the HP condenser cooling needs by the RCE cooling production implies only 20% savings in the HP electricity consumption (associated to the 25% improvement of the COP mentioned before), not the ideal 100% electricity replacement if the temperature levels produced in the RCE were suitable for the food industry needs.

Third, the sizing of the RCE field is carried out for these extreme cases:

1. dimensioning the RCE field for covering all the warm water industry loads in the month with the highest solar radiation (heat tracking sizing).
2. dimensioning the RCE field to cover all the heat pump condenser cold needs associated to the industry cooling requirements in the month with the highest radiative cooling potential (cold tracking sizing).

Note that the cooling needs of the condenser are higher than the refrigeration output in the evaporator of the heat pump, as the condenser needs to dissipate both the evaporator load and the compressor work. For example, if we assume a HP cooling COP of 3, the condenser cooling load is 133.3% bigger than the evaporator cooling production.

Finally, once the two RCE sizing are determined, the monthly heating and cooling coverages of the RCE field (RCE heating and cooling fractions) are calculated, and final energy, primary energy and cost savings are compared with the base case of no RCE integration. Table 2 shows several estimated input data required in the calculations, such as HP refrigeration COP, natural gas boiler efficiency, RCE efficiencies, industry Spanish costs for natural gas and electricity and Spanish pass factors from final to primary energy:

Tab. 2: Input data used for energy and cost savings estimations.

Boiler average annual efficiency	HP cooling average annual efficiency	RCE average annual heating efficiency	RCE average annual cooling efficiency	Cost natural gas (€/kWh) *	Cost electricity (€/kWh) **	Conversion factor from final energy to primary energy, Electricity ***	Conversion factor from final energy to primary energy, Natural Gas ***
0.9	3	0.6	0.4	0.05	0.092	2.403	1.195

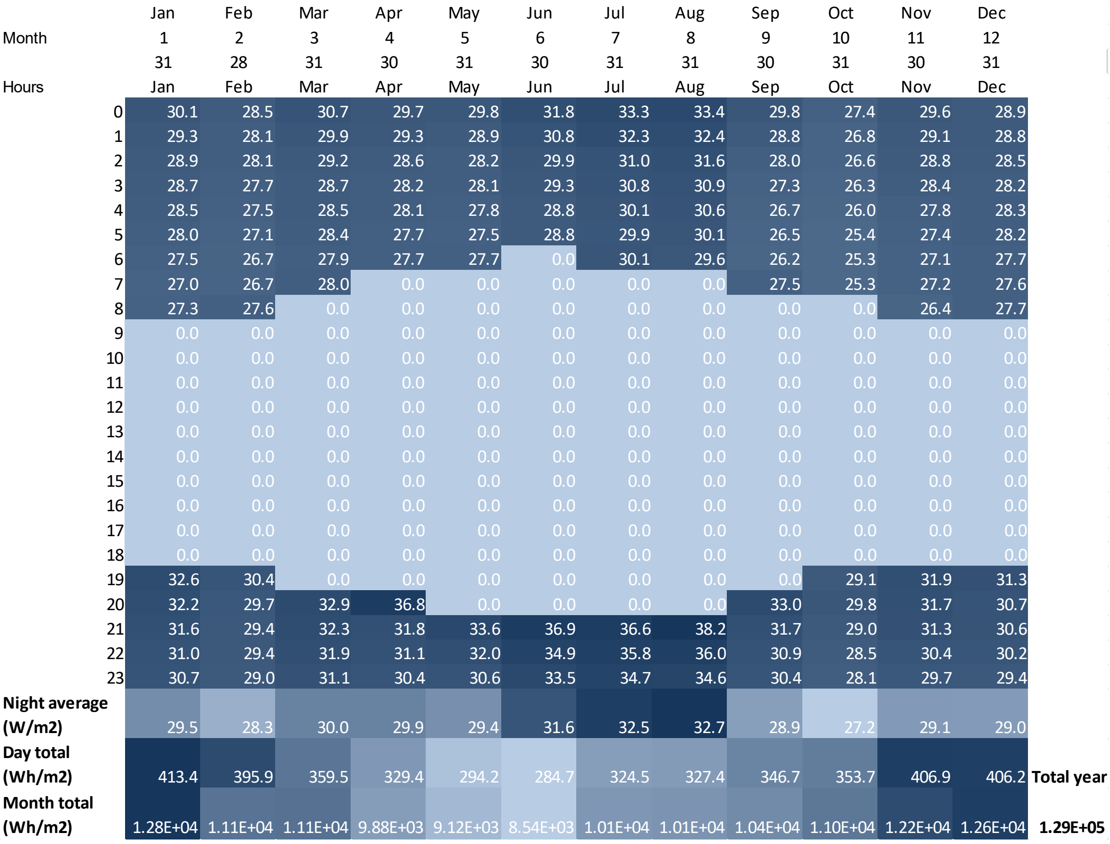
* ("Precio del kWh de gas natural 2019," n.d.)

** ("PRECIO NETO DE LA ELECTRICIDAD DE USO INDUSTRIAL….," 2021)

*** ("Ministerio para la Transición Ecológica y el Reto Demográfico - Documentos reconocidos," n.d.).

3. Results and discussion

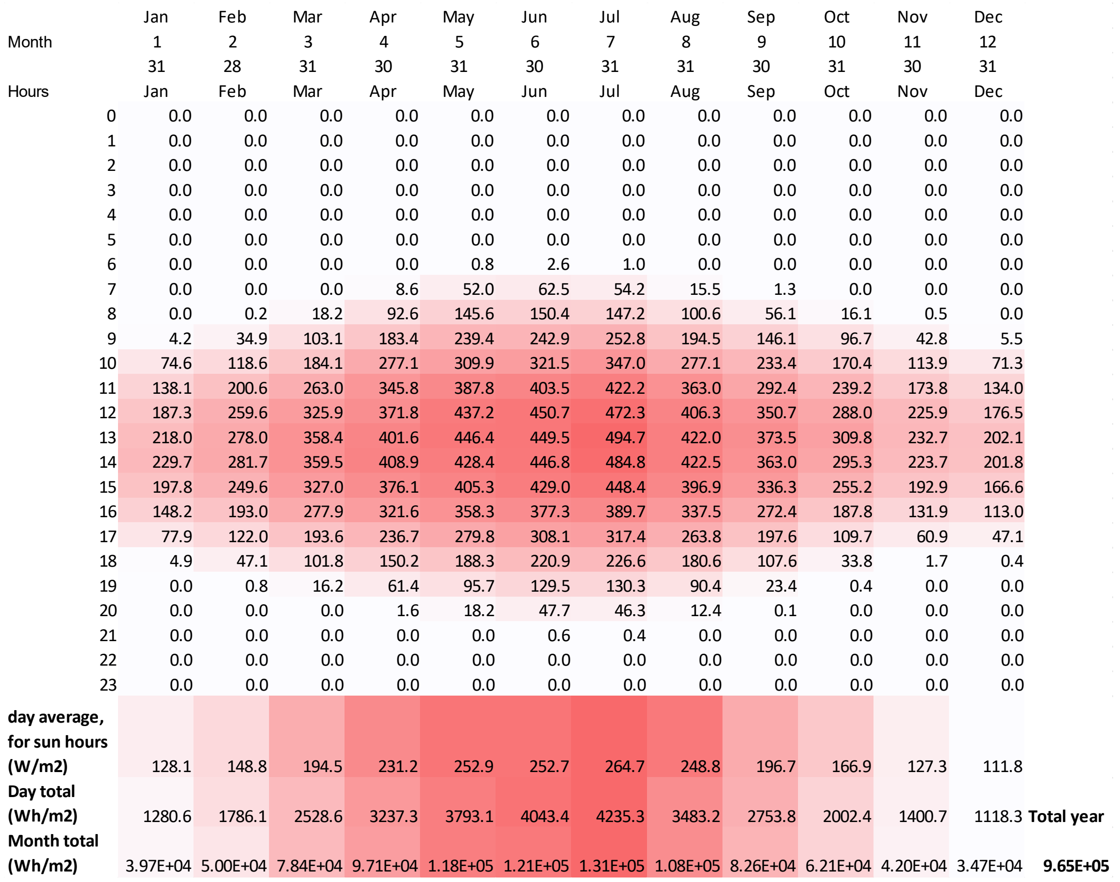
Estimated values for hourly, monthly and annual RCE cold (Figure 1) and RCE heat (Figure 2) generation are presented for Barcelona, as example of results. Similar tables have been generated for the other two Spanish cities in study.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Month	1	2	3	4	5	6	7	8	9	10	11	12	
	31	28	31	30	31	30	31	31	30	31	30	31	
Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
0	30.1	28.5	30.7	29.7	29.8	31.8	33.3	33.4	29.8	27.4	29.6	28.9	
1	29.3	28.1	29.9	29.3	28.9	30.8	32.3	32.4	28.8	26.8	29.1	28.8	
2	28.9	28.1	29.2	28.6	28.2	29.9	31.0	31.6	28.0	26.6	28.8	28.5	
3	28.7	27.7	28.7	28.2	28.1	29.3	30.8	30.9	27.3	26.3	28.4	28.2	
4	28.5	27.5	28.5	28.1	27.8	28.8	30.1	30.6	26.7	26.0	27.8	28.3	
5	28.0	27.1	28.4	27.7	27.5	28.8	29.9	30.1	26.5	25.4	27.4	28.2	
6	27.5	26.7	27.9	27.7	27.7	0.0	30.1	29.6	26.2	25.3	27.1	27.7	
7	27.0	26.7	28.0	0.0	0.0	0.0	0.0	0.0	27.5	25.3	27.2	27.6	
8	27.3	27.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.4	27.7	
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
19	32.6	30.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.1	31.9	31.3	
20	32.2	29.7	32.9	36.8	0.0	0.0	0.0	0.0	33.0	29.8	31.7	30.7	
21	31.6	29.4	32.3	31.8	33.6	36.9	36.6	38.2	31.7	29.0	31.3	30.6	
22	31.0	29.4	31.9	31.1	32.0	34.9	35.8	36.0	30.9	28.5	30.4	30.2	
23	30.7	29.0	31.1	30.4	30.6	33.5	34.7	34.6	30.4	28.1	29.7	29.4	
Night average (W/m2)	29.5	28.3	30.0	29.9	29.4	31.6	32.5	32.7	28.9	27.2	29.1	29.0	
Day total (Wh/m2)	413.4	395.9	359.5	329.4	294.2	284.7	324.5	327.4	346.7	353.7	406.9	406.2	**Total year**
Month total (Wh/m2)	1.28E+04	1.11E+04	1.11E+04	9.88E+03	9.12E+03	8.54E+03	1.01E+04	1.01E+04	1.04E+04	1.10E+04	1.22E+04	1.26E+04	**1.29E+05**

Fig. 1: Average hourly, daily and monthly cooling RCE production at nights for Barcelona (Spain).

It is observed that the average cooling power in nighttime hours is slightly higher in summer months, although the total monthly cold production is about 40% larger in winter months, as more night hours are available. A total annual cold production of 129 kWh/m^2 is achievable. Note also that during daytime there is no production of radiative cooling in this study, as solar collection is preferred in daily hours, to meet industry heat needs. During the day, in solar thermal collector mode (Figure 2), both the average heat power and the monthly thermal energy production are much higher in summer months. This difference between winter and summer months is even larger than in a typical inclined solar collector, as the RCE is positioned in horizontal position, to maximize the night radiative cooling production. A total annual heat of 965 kWh/m^2 is produced. The ratio of heating over cooling RCE production, η_{RCE}, is 7.5. Figure 3 shows the comparison of the RCE combined heating and cooling production in the three selected Spanish cities.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Month	1	2	3	4	5	6	7	8	9	10	11	12	
	31	28	31	30	31	30	31	31	30	31	30	31	
Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
6	0.0	0.0	0.0	0.0	0.8	2.6	1.0	0.0	0.0	0.0	0.0	0.0	
7	0.0	0.0	0.0	8.6	52.0	62.5	54.2	15.5	1.3	0.0	0.0	0.0	
8	0.0	0.2	18.2	92.6	145.6	150.4	147.2	100.6	56.1	16.1	0.5	0.0	
9	4.2	34.9	103.1	183.4	239.4	242.9	252.8	194.5	146.1	96.7	42.8	5.5	
10	74.6	118.6	184.1	277.1	309.9	321.5	347.0	277.1	233.4	170.4	113.9	71.3	
11	138.1	200.6	263.0	345.8	387.8	403.5	422.2	363.0	292.4	239.2	173.8	134.0	
12	187.3	259.6	325.9	371.8	437.2	450.7	472.3	406.3	350.7	288.0	225.9	176.5	
13	218.0	278.0	358.4	401.6	446.4	449.5	494.7	422.0	373.5	309.8	232.7	202.1	
14	229.7	281.7	359.5	408.9	428.4	446.8	484.8	422.5	363.0	295.3	223.7	201.8	
15	197.8	249.6	327.0	376.1	405.3	429.0	448.4	396.9	336.3	255.2	192.9	166.6	
16	148.2	193.0	277.9	321.6	358.3	377.3	389.7	337.5	272.4	187.8	131.9	113.0	
17	77.9	122.0	193.6	236.7	279.8	308.1	317.4	263.8	197.6	109.7	60.9	47.1	
18	4.9	47.1	101.8	150.2	188.3	220.9	226.6	180.6	107.6	33.8	1.7	0.4	
19	0.0	0.8	16.2	61.4	95.7	129.5	130.3	90.4	23.4	0.4	0.0	0.0	
20	0.0	0.0	0.0	1.6	18.2	47.7	46.3	12.4	0.1	0.0	0.0	0.0	
21	0.0	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.0	0.0	0.0	0.0	
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
day average, for sun hours (W/m2)	128.1	148.8	194.5	231.2	252.9	252.7	264.7	248.8	196.7	166.9	127.3	111.8	
Day total (Wh/m2)	1280.6	1786.1	2528.6	3237.3	3793.1	4043.4	4235.3	3483.2	2753.8	2002.4	1400.7	1118.3	**Total year**
Month total (Wh/m2)	3.97E+04	5.00E+04	7.84E+04	9.71E+04	1.18E+05	1.21E+05	1.31E+05	1.08E+05	8.26E+04	6.21E+04	4.20E+04	3.47E+04	**9.65E+05**

Fig. 2: Average hourly, daily and monthly heating RCE production during the day for Barcelona (Spain).

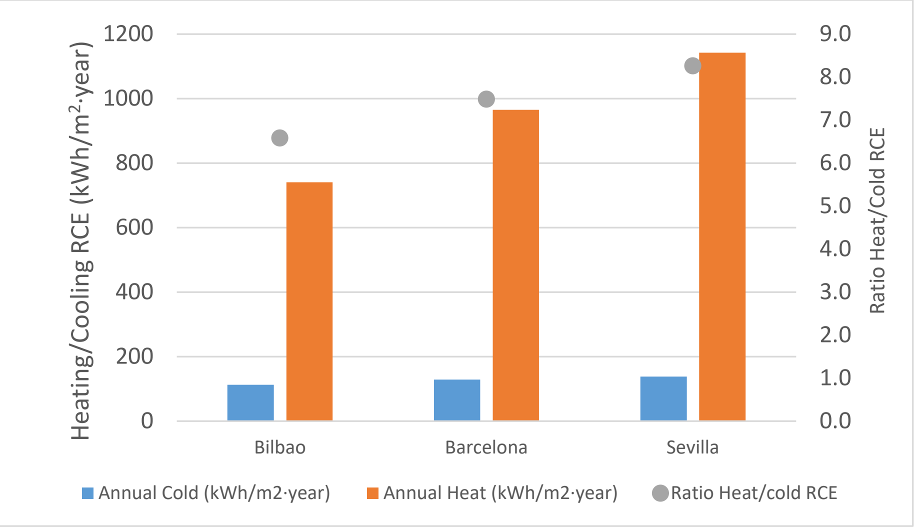


Fig. 3: Annual Heating and Cooling RCE production in Bilbao, Barcelona and Sevilla (Spain).

Sevilla's weather, with more clear days and nights than Bilbao, implies a 54% increase in RCE heating generation and 23% more cooling production. Barcelona is in between, with 30% more heating and 15% more cooling. Regarding the RCE heating over cooling ratios, the values for Sevilla, Barcelona and Bilbao are 8.3, 7.5 and 6.6, respectively.

The above presented RCE heating over cooling production ratios will be compared with the previously presented food industry ratios for warm water demands over condenser cooling needs (see Table 3). The more similar are these two ratios, the more cost-effective will be the investment in the RCE field, as less RCE production will be wasted and more energy needs will be covered with renewable energy. The juice canning process is the one with the best match ($\eta_{warm,cond}$ = 7.8), while the other food industries show much smaller ratios (between 0.1 to 2.3) than the RCE production ratios (between 6.6 and 8.3). The second-best match is vegetable and fruit canning, with η_{RCE}=2.3. This mismatch means that if the RCE field is matching the warm water loads (sizing Heat), only a small part of the condenser cooling needs will be covered by the RCE cooling, and the electricity savings will be limited. Primary energy savings will be in this case comparable with the savings produced by a field with the same number of solar collectors, with a modest extra primary savings due to the displaced electricity in the HP for the small part of the day in which the RCE cold production can cover the condenser demands. On the other hand, if the RCE field is dimensioned for covering the condenser cooling loads (sizing Cold), a much larger number of RCE devices are required and a considerably bigger investment and longer paybacks are expected. Besides, this cold tracking sizing will generate a large excess of heating, which will be wasted, unless it could be sold to a nearby industry or city. Moreover, larger primary energy and annual cost savings are expected with this sizing, as all the natural gas consumption in the boiler will be displaced by the RCE heating production, and the maximum possible electricity displacement in the HP compressor consumption will be also achieved (20% for a HP COP = 3).

Tab. 3: Comparison between heat over cold demands ratios in food industry and the expected RCE production ratios.

Industry process	Ratio Warm Water /Condenser Cooling industry, $\eta_{warm,cond}$	Ratio Heating/Cooling RCE, η_{RCE}
Beer brewing	0.9	6.6 - 8.3
Milk	0.1	6.6 - 8.3
Cheese processing	0.4	6.6 - 8.3
Vegetable and fruits canning	2.3	6.6 - 8.3
Juice canning	7.8	6.6 - 8.3
Poultry slaughtering	0.2	6.6 - 8.3

Figure 4 shows the monthly percentage of warm water needs covered by the RCE production in Barcelona. As the heat tracking dimensioning is done for the month with the largest solar radiation, in winter months the coverage is below 40%. The coverage in July is slightly above 100% due to the rounding-up in sizing the number of RCE units. Figure 5 shows the monthly percentage of condenser cooling needs covered by the RCE production in Barcelona, with the same heat tracking sizing. As anticipated before, only the two canning processes can cover an important amount (above 20%) of their condenser cooling needs. The rest of the food industries included in this study are below 10% for RCE condenser cooling coverage. Similar plots are generated for Seville and Bilbao with similar final results.

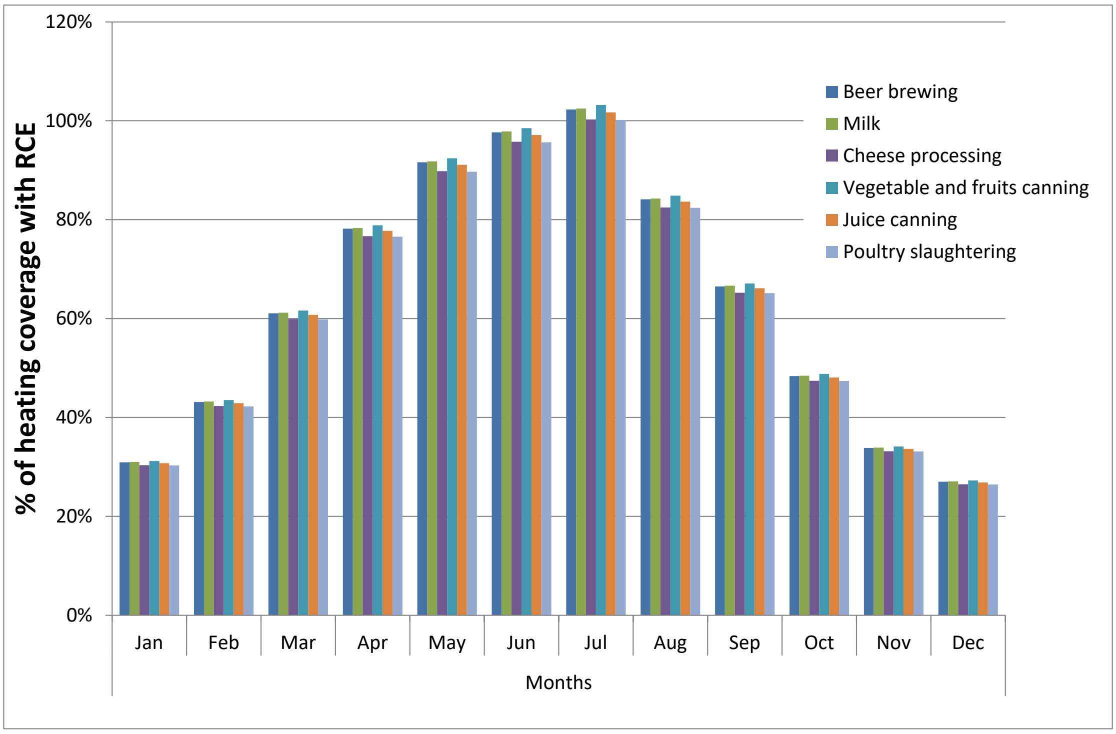


Fig. 4: Monthly coverage of food industry warm water with RCE field for heat tracking sizing in Barcelona.

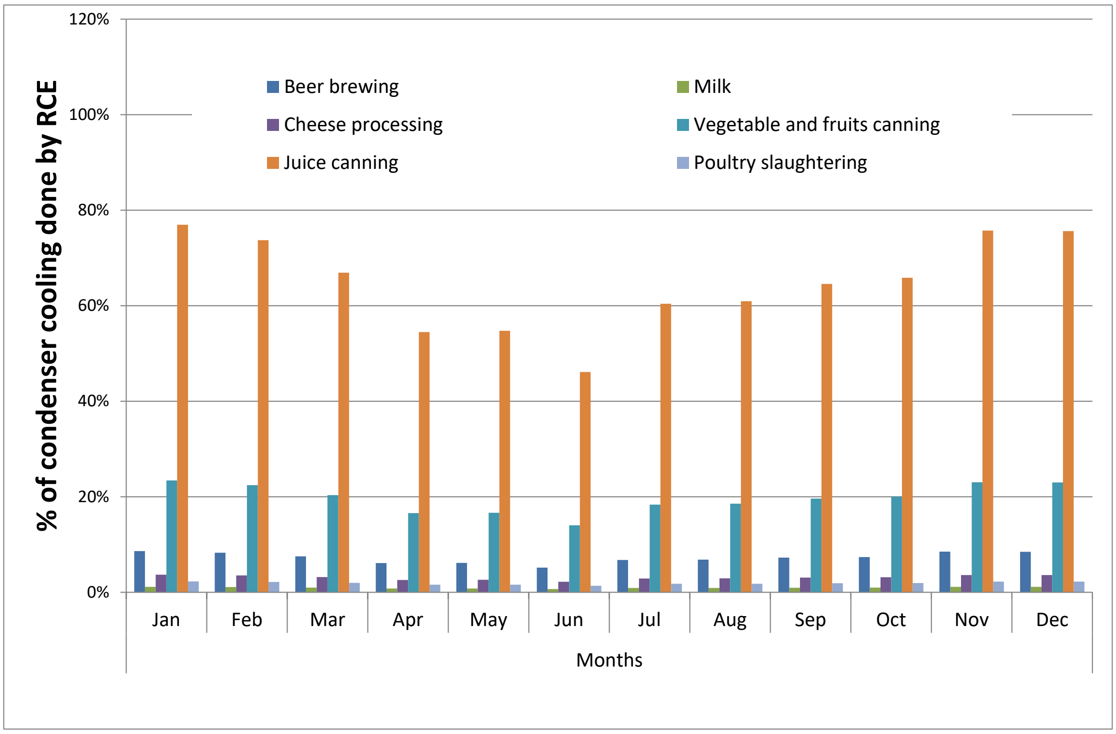


Fig. 5: Monthly coverage of food industry condenser cooling with RCE field for heat tracking sizing in Barcelona.

In Figure 6 the percentages of monthly cold coverage when the RCE field is tracking the HP condenser cooling needs are presented. Contrary to the previous case, now the number of RCEs is much bigger, and the percentage of condenser cooling covered by the RCE is much higher. However, the monthly RCE generation of warm water is well above the warm water needs of all the food industries, so 100% coverage is reached every month, but most of the generated solar heat is wasted (figure not shown).

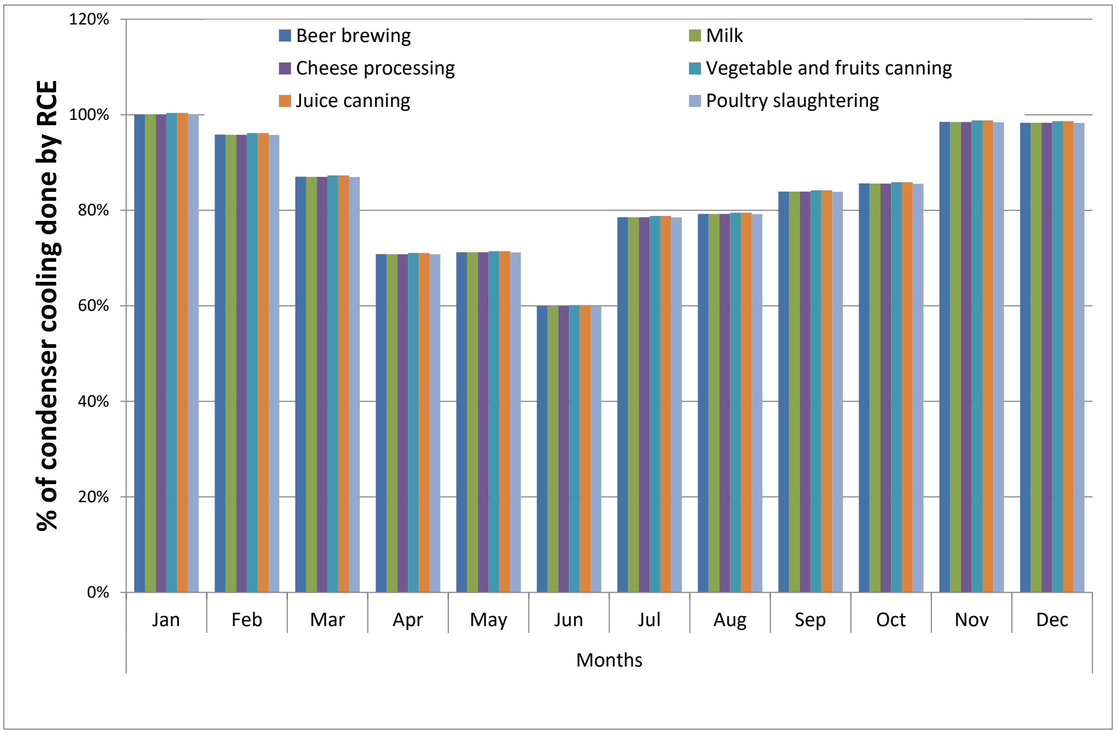


Fig. 6: Monthly coverage of food industry HP condenser cooling with RCE field for tracking cold sizing.

A reference value of 1 million kg of product per year is considered for the dimensioning exercise as base of calculation. Table 4 presents the percentages of total heat, warm water, HP cooling savings as well as the number of RCE needed in Barcelona for the two selected sizing options: 1) tracking warm water needs (fewer number of RCEs); and 2) tracking condenser cooling needs (greater number of RCE units). The final number of RCE units depends on the location/climate and the sizing, as expected. Putting the focus on juice canning, the food industry best fitting the RCE integration, and in the case of tracking heat, Sevilla needs only 39 units, Barcelona 46 (Table 4), and Bilbao 59. So, better paybacks are expected in Sevilla, as the same renewable heat and cold production can be achieved with less initial investment. The final number of RCE units needed is between 1 to 2 orders of magnitude bigger for the condenser cooling needs tracking case for most of the industries, with the exception of the juice canning industry, where the two sizing results are comparable (46 units for heat tracking, and 60 for cold tracking). Other important aspects can be highlighted: the heating savings can only go up 50%, as the other half of the heating needs is at higher temperature and a boiler is still needed. Furthermore, the maximum electricity savings are poor, as we are not able to displace the cooling needs directly with the RCE, but only improve the cooling HP COP thanks to the reduction of condenser working temperature. Similar results are found for Seville and Bilbao.

Tab. 4: Differences in sizing the RCE field for tracking heat needs or tracking cold needs in Barcelona.

	RCE Sizing Tracking Warm Water needs				RCE sizing Tracking Condenser Cooling Needs			
Industry process	**% total heat RCE**	**% Warm Water RCE**	**% HP cooling electric savings RCE**	**No RCEs**	**% total heat RCE**	**% Warm Water RCE**	**% HP cooling electric savings RCE**	**No RCEs**
Beer brewing	31.9%	63.7%	1.5%	**34**	50.0%	100.0%	17%	**393**
Milk	31.9%	63.8%	0.2%	**13**	50.0%	100.0%	17%	**1111**
Cheese processing	31.2%	62.5%	0.6%	**61**	50.0%	100.0%	17%	**1649**
Vegetable and fruits canning	32.1%	64.3%	3.9%	**28**	50.0%	100.0%	17%	**120**
Juice canning	31.7%	63.4%	12.9%	**46**	41.3%	82.6%	17%	**60**
Poultry slaughtering	31.2%	62.4%	0.4%	**81**	50.0%	100.0%	17%	**3536**

Figure 7 shows the comparison of the annual energy costs (warm water and cooling) for the 6 food industries in study. Other high temperature heating costs which cannot be replaced by RCE or other electric costs not associated to cooling needs are not considered in our simulation. Together with the base case costs, costs for the two sizing scenarios (heat and cold tracking) are also presented. Results shown are for Barcelona, but very similar results are obtained for the other two cities under study. The most energy intensive food industries are poultry slaughtering (52,000€ in energy costs for an annual production of 1 million kg of product) and cheese processing (32,000€). Vegetable canning (10,000€) and milk (12,000€) process show the smaller energy costs in the base cases. Dimensioning the RCE field for covering warm water needs (Heat tracking case) brings important cost savings. Absolute cost savings happen in the most energy intensive food industries, 17,000€ in poultry slaughtering and 13,000€ in cheese processing. The contribution of electricity cooling cost savings in this case is very small, below 1%. In relative values, the range of cost savings is between 23% and 62%. As discussed above, the largest cost savings in relative terms occur for juice canning process (62%), as its heat and cold needs matches the heat and cold production of the RCE (see Table 3). Even larger cost savings are observed for the condenser cooling tracking case, as many more RCE units are put in the system, and all the industry heating needs are covered in this case. About 32,000€ and 23,000€ can be saved in poultry slaughtering and cheese processing, respectively. For this case the electricity cost savings are noticeable, contributing about 10% of the total savings. Relatively speaking, important percentages of cost reductions are observed for all food industries, ranging from 47% for milk industry up to 93% for vegetables and fruits canning. However, these bigger cost savings are associated to a much bigger initial investment in the RCE field, which discards its economic viability. Assuming a turn key investment cost for the RCE field of 770 €/m^2 (“Europe,” n.d.), reasonable payback periods of 7.2 years are obtained for the heat tracking case.

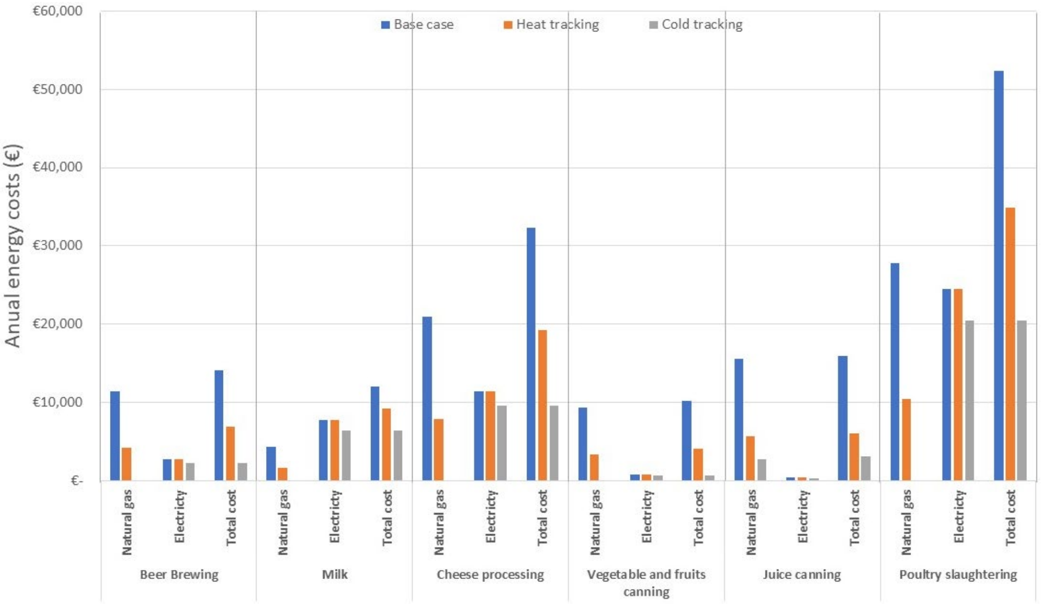


Fig. 7: Annual energy costs for base case, RCE heat tracking and RCE cold tracking in Barcelona.

Table 5 presents the summarized data of primary energy and cost savings in relative terms for the 6 food industries in the three Spanish locations in study. The three cities show very similar results, with differences in cost and primary energy savings of less than 1%. As expected, Sevilla location outperforms Barcelona, and Barcelona has slightly better results than Bilbao. On the other hand, there would be important differences in initial investments due to different sizing results, as stated previously. Cost savings are between 1 or 2 points above primary energy savings, reflecting the higher cost per kwh of electricity over natural gas.

Tab. 5: Primary energy and cost savings in food industry for RCE sizing in heat tracking and cold tracking cases.

		Heat tracking						Cold tracking					
		Primary enegy savings (%)			*Cost savings (%)*			*Primary enegy savings (%)*			*Cost savings (%)*		
Sevilla	**Industry**	**Gas**	**Elec.**	**Total**	**Gas**	**Elec.**	**Total**	**Gas**	**Elec.**	**Total**	**Gas**	**Elec.**	**Total**
	Beer brewing	64.3%	1.4%	51.3%	64.3%	1.4%	52.2%	100.0%	18.1%	83.1%	100.0%	18.1%	84.2%
	Milk	63.9%	0.2%	21.9%	63.9%	0.2%	23.2%	100.0%	18.1%	46.0%	100.0%	18.1%	47.7%
	Cheese processing	64.3%	0.6%	40.4%	64.3%	0.6%	41.7%	100.0%	18.1%	69.3%	100.0%	18.1%	71.0%
	Vegetable and fruits canning	65.2%	3.7%	59.8%	65.2%	3.7%	60.2%	100.0%	18.2%	92.7%	100.0%	18.2%	93.3%
	Juice canning	63.6%	12.0%	62.1%	63.6%	12.0%	62.2%	96.2%	18.2%	94.0%	96.2%	18.2%	94.2%
	Poultry slaughtering	63.8%	0.4%	32.7%	63.8%	0.4%	34.1%	100.0%	18.1%	59.7%	100.0%	18.1%	61.6%
Barcelona		**Heat tracking**						**Cold tracking**					
		Primary enegy savings (%)			*Cost savings (%)*			*Primary enegy savings (%)*			*Cost savings (%)*		
	Industry	**Gas**	**Elec.**	**Total**	**Gas**	**Elec.**	**Total**	**Gas**	**Elec.**	**Total**	**Gas**	**Elec.**	**Total**
	Beer brewing	63.7%	1.5%	50.8%	63.7%	1.5%	51.7%	100.0%	16.8%	82.8%	100.0%	16.8%	84.0%
	Milk	63.8%	0.2%	21.9%	63.8%	0.2%	23.2%	100.0%	16.8%	45.2%	100.0%	16.8%	46.9%
	Cheese processing	62.5%	0.6%	39.3%	62.5%	0.6%	40.6%	100.0%	16.8%	68.9%	100.0%	16.8%	70.6%
	Vegetable and fruits canning	64.3%	3.9%	58.9%	64.3%	3.9%	59.4%	100.0%	16.9%	92.6%	100.0%	16.9%	93.2%
	Juice canning	63.4%	12.9%	61.9%	63.4%	12.9%	62.1%	82.6%	16.9%	80.8%	82.6%	16.9%	80.9%
	Poultry slaughtering	62.4%	0.4%	31.9%	62.4%	0.4%	33.3%	100.0%	16.8%	59.1%	100.0%	16.8%	61.0%
Bilbao		**Heat tracking**						**Cold tracking**					
		Primary enegy savings (%)			*Cost savings (%)*			*Primary enegy savings (%)*			*Cost savings (%)*		
	Industry	**Gas**	**Elec.**	**Total**	**Gas**	**Elec.**	**Total**	**Gas**	**Elec.**	**Total**	**Gas**	**Elec.**	**Total**
	Beer brewing	63.3%	1.7%	50.6%	63.3%	1.7%	51.4%	100.0%	16.2%	82.7%	100.0%	16.2%	83.9%
	Milk	64.1%	0.2%	22.0%	64.1%	0.2%	23.3%	100.0%	16.2%	44.8%	100.0%	16.2%	46.5%
	Cheese processing	62.1%	0.7%	39.1%	62.1%	0.7%	40.4%	100.0%	16.2%	68.6%	100.0%	16.2%	70.3%
	Vegetable and fruits canning	63.5%	4.5%	58.2%	63.5%	4.5%	58.6%	100.0%	16.2%	92.6%	100.0%	16.2%	93.2%
	Juice canning	62.4%	14.8%	61.1%	62.4%	14.8%	61.2%	68.7%	16.4%	67.3%	68.7%	16.4%	67.4%
	Poultry slaughtering	62.1%	0.4%	31.8%	62.1%	0.4%	33.2%	100.0%	16.2%	58.8%	100.0%	16.2%	60.7%

Finally, Figure 8 illustrates graphically some of the results presented in Table 5. Namely, the percentage of primary energy savings in Barcelona is plotted for the six industries in study for the RCE heat tracking case. Food industries are arranged in descending order of savings, with milk (22% savings) at the top and juice canning (62% savings) at the bottom. As said before, differences among cities are very small, in the range 0-1%. In the same graph the warm water over condenser cooling needs ratios, $\eta_{\text{warm,cond}}$, is included, in the upper horizontal axis. This is to visualize again the correlation between the similarity of RCE (η_{RCE}) and industry ($\eta_{\text{warm,cond}}$) heat/cold ratios and the achieved energy and cost savings. For instance, in the milk process, ($\eta_{\text{warm,cond}} = 0.1$ vs. η_{RCE} for Barcelona = 7.5), the cooling needs in the condenser are 10 times bigger than the ones for heating. Thus, when the RCE field is covering most of the heating needs, most of the electric needs for cooling are still there, achieving only 22% of total primary energy savings. On the other hand, in the juice canning case ($\eta_{\text{warm,cond}} = 7.8$), there is an almost perfect match with the η_{RCE} for Barcelona (7.5). This implies that the RCE field covers an important part of the heating needs (Figure 4) and covers also most of the condenser cooling needs (Figure 5), contributing with almost 13% in electricity cooling savings. Thus, total primary savings reach 62% for this industry.

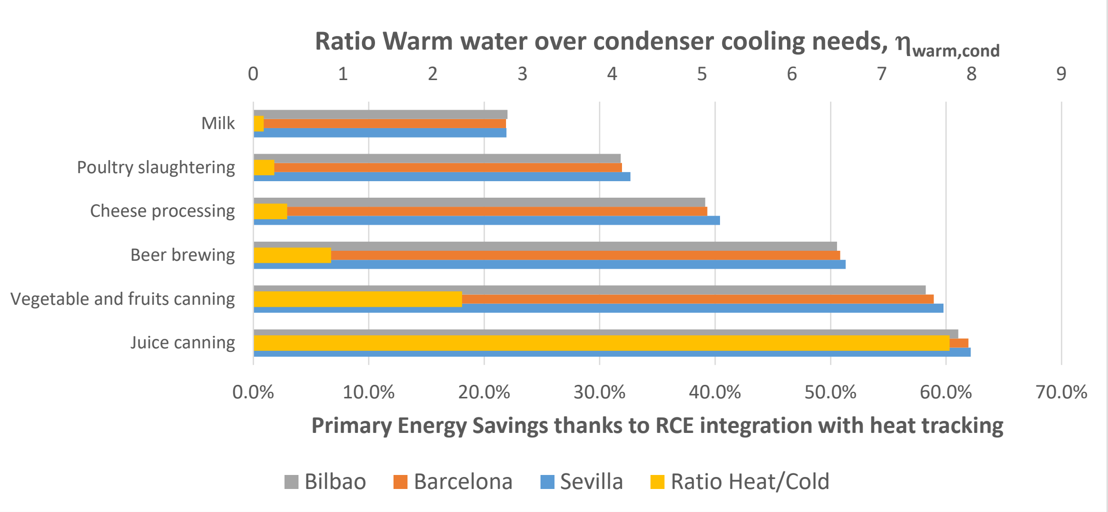


Fig. 8: Primary energy savings in food industry for the RCE heat tracking case in the Bilbao, Barcelona and Seville.

4. Conclusions

The potential of the integration of a novel renewable heating and cooling technology (RCE) in seven food industries (beer brewing, food pasteurization, milk processing, cheese processing, vegetal and fruits canning, juice canning and poultry slaughtering) has been studied. Two different sizing matching the heat needs and the cooling needs have been considered. The number or RCE devices depend on the location and is for the two considered scenarios very different, with larger investment for the cooling sizing. Comparing the ratios of heating over cooling loads in several processes with the ratios of RCE heat and cold production, best matches are found for vegetable and fruits and juice canning industries. Moreover, primary energy savings reach 62% for the juice canning industry as the RCE field covers an important part of the heating and of the condenser cooling needs.

5. Acknowledgments

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