Renewable heat for the fulfillment of the cooling demand in the fruit and vegetable processing and preserving industries in the intensive agriculture: a case study in Southern Spain

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Abstract

The post-harvest processing at fruit and vegetable pack-houses and logistic centers (FVPLC) in locations where, as it occurs in Southern Spain, these facilities and greenhouses co-exist in a dense and interconnected environment constitute an interesting field for the application of renewable sources of energy. The availability and conscious management of solar radiation, necessary for driving the greenhouses food production, as well as the availability of biomass, both in the form of plants wastes and, eventually, in the form energy crops allow to advance a high potential for the use of these renewable heat sources in such agro-industrial cluster constituted by greenhouses, FVPLC and auxiliary industries. In this work, it is carried the estimation of the values of some specific technical and environmental indexes of performance of the cold stores that are part of these facilities under two energy supply scenario: a conventional mains scenario and an alternative scenario in which cooling demand is fulfilled by thermally driven absorption devices. Cooling loads at regional and facility levels, the last thanks to the access to actual case studies, have been evaluated and used as input for the estimation and analysis of the following indexes under the two advanced scenarios: annual energy consumption, specific electricity consumption for cooling and equivalent CO_2 emissions.

Keywords: Renewable heat, absorption cooling, post-harvest processing

1. Introduction

Southeastern Spain is one of the European more relevant food producer areas having an average annual yield of more than 3 million of tons of, mainly, tomato but also pepper, cucumber, eggplant, zucchini, melon and watermelon. This plants production results, only in terms of exports, in a turnover of more than 2500 M€ and accounts for 24% of the gross domestic product and 28% of employment of the region (Galdeano-Gómez, et al., 2017) The magnitude of these figures has been reached thanks to intensive cropping techniques applied in approximately 40.000 ha of greenhouses, most of them located in coastal areas in the provinces of Almería, mainly, Granada, Málaga and Murcia. In this context, the energy demand of the cold stores for crops conservation, both during post-harvest and commercialization phases, despite being well identified because its relevance for the preservation of the food properties and for the design and operation of the systems, is a scarcely investigated field for the application of renewable sources. This became especially interesting if we consider these processes as a part of a higher level agro-industrial productive district in which the renewable energies could play an important role and in which the on-going environmental impact analyses are mainly devoted to the plants growing processes - indoor climatic control, irrigation,…- but no, at least at the same level, to the rest productive stages. (van der Werf et al., 2014; Torrellas et al., 2013)

It is estimated that in Europe there are $60\cdot10^6$-$70\cdot10^6$ m^3 of food cold storage (Fikiin et al., 2017) Worldwide, it has been also estimated that this sector is responsible for 20% of the total food industry electrical energy consumption. Specific surveys on the above have shown a considerable variation between different facilities, largely related, as it could be expected, to the size and location of the warehouses, storage temperatures and product loads (Swain, 2009; Elleson and Freund, 2004)

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For the case of Spain, food processing industries account for 15% of national energy consumption, being that percentage 20% for Andalusia region (Southern Spain). According GRIA (2013) also in Andalusia there are about 740 FVPLC centers being Almería the province with the largest number of these facilities, with almost one third of the total (Figure 1). Cooling installations at these FVPLC facilities are mostly 1) pre-refrigeration stores (9%), 2) refrigeration stores (70%) and 3) rapid tunnel cooling (10%) having an average installed power of 565 kW and a consumption of 294 MWh/year (Figure 2)

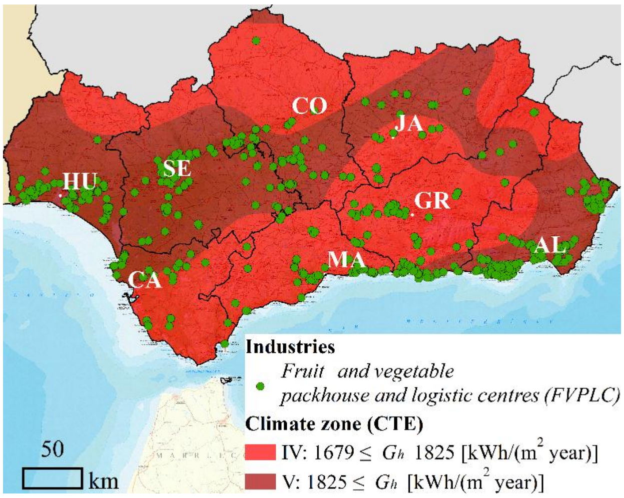

Fig. 1: Fruit and vegetable packhouses and logistic centres (FVPLC) and the radiation climate zones in Andalusia

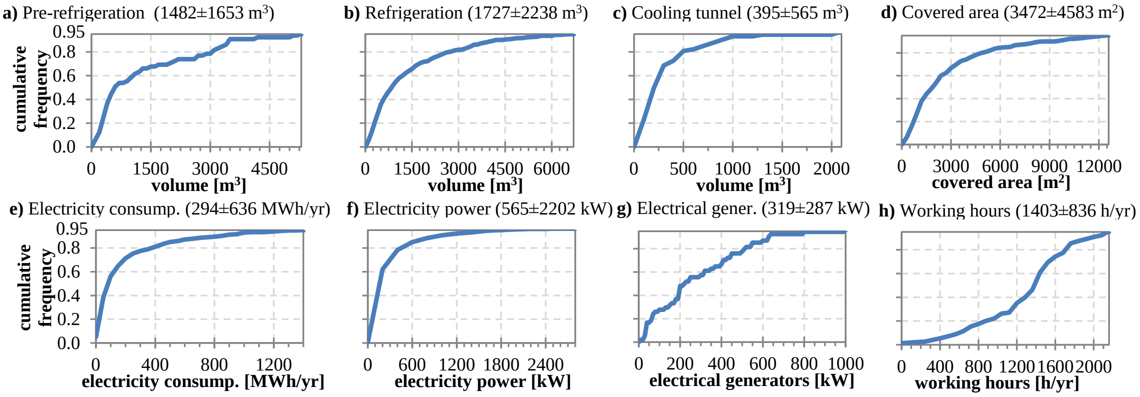

Fig. 2: Characterization of the horticultural industries in Andalusia (GRIA, 2011)

In this work it is analyzed the potential of the application of renewable heat for the cooling of the post-harvest products in these FVPLC facilities, which are located, as advanced, in an extremely dense area of greenhouse farms. The goal of the analysis is to contribute to the assessment and further reduction of the environmental impacts of the processes involved in the greenhouses production agroindustry no directly related to the cultivation ones. We have selected a representative case study based on actual data of a FVPLC at Almería's province. After establishing the energy demands related to cooling processes, the estimation of the specific indexes annual energy consumption, specific electricity consumption for cooling and CO_2 emissions for two energy supply scenario has been carried out. The first scenario is the present one, the use of the available mains for feeding compression chillers. The second scenario is the use of renewable sources provided both by solar energy and biomass for feeding heat driven absorption cooling devices. Greenhouses exploitations are located in sunny areas, as it is the case of Almería's province (Figure 1) and crops residues are a well characterized source of biomass (Callejón-Ferre et al., 2011). While photovoltaic solar energy could be also considered, this work has been focused to thermally driven options because the actual possibility of continuous renewable operation of the systems thanks to thermal storage. In upcoming works, a more complete approach will be tackled under the emerging paradigm distributed energy networks for agro-industrial districts, including photovoltaics (Schweiger et al., 2018)

2. Case studies

2.1. Case study

This work uses as reference two FVPLC industries -denominated Case A and Case B - processing 126.000 t/yr of vegetables during the studied period. This production comes from a crop area of 915 has, of which 92% are crops grown under plastic greenhouses in Almería following typical cultivation cycles and 8% are summer crops in mesh greenhouses. These two industries account for approximately 6% of the total vegetable crop production tested in the Almeria region. In order to increase the pertinence of solar option, we have considered a third case (Case C), in which production has increased over central months resulting in constant production throughout the year. This case assumes that consumption could better fit solar availability in summer, increasing the load thanks to outdoor mesh tomato contribution produced in other areas.

Both A and B facilities have cold room volumes of about 12.000 m^3, divided equally between the refrigeration and pre-refrigeration zones. The industry has an installed overall power of 980 kWe. The cooling facility A is devoted to tomato, pepper, cucumber, eggplant and melon processing and the cooling facility B is exclusively devoted to tamato (Table 1). In spite of the actual data of the electricity and fuel-oil annual energy consumptions are known, 3,7 MWh and 0,4 MWh respectively, as usual in many industries, they do not discriminate the corresponding particular uses (lighting, cooling, engines,...). Therefore, an indirect estimation is necessary to evaluate the specific thermal load of the cooling chambers, $\dot{Q}_{ref}$, the load which is necessary to maintain the temperature within the design point. Once $\dot{Q}_{ref}$ is estimated, its integration on a daily and yearly basis allows also to estimate of the energy demand for refrigeration, E_{ref}. The values of E_{anual} in terms of electricity or heat, for the case of thermally driven devices, are calculated by corresponding systems coefficients of performance values $SCOP$.

In both cases the daily and monthly product patterns have been considered and the loads for the pre-refrigeration and refrigeration processes. The following input quantities have been used: the processed product by the FVPLC, the climate data, the cold room characteristics and, finally, the length, sequence and features of the processes (ASHRAE, 2010; Trott and Welch, 2000; Ballard, 1992), b). Hourly climate data for a typical meteorological year generated using Meteonorm v.7 were used as the reference for the location of the case studies - in which the average temperature was 18.0±6.0 °C, relative humidity 65.0±14.0 %, wind speed 4.0±2.4 m/s and a yearly accumulated horizontal solar radiation 1.861 kWh/(m^{2}yr).

Tab. 1: Crops production by case study

Case	Refrigerated production		Crop area		Summer crop (tomato)		Energy consumption
	[t/yr]	Products	[ha]	Products	[t/yr]	[ha] [%]	[MWh/yr]
A	68.304	tomato (33%), pepper (27%), cucumber (19%), eggplant (14%), melon (7%)	491	to. (32%), pe. (37%), cu. (17%), eg. (14%)	1.972	15 (3%)	electrical: 3.700(90%) fuel oil: 402 (10%)
B	57.328	tomato (100%)	424	to. (100%)	7.571	56 (13%)	
C	76.432	tomato (100%)	561	to. (100%)	26.177	194 (34%)	

2.1. Energy indexes

For refrigeration facilities, the Total Equivalent Warming Impact index, $TEWI$, provides specific information of refrigeration systems environmental impact because, together to the indirect effect due to the impact of CO$_2$ emissions from fossil fuels used to generate the energy to operate the equipment throughout its lifetime, it takes into account the direct warming effect due to the refrigerant gases released during equipment operation, including unrecovered losses (Wu et al., 2013; AIRAH, 2012). It is measured in units of mass in kg of carbon dioxide equivalent (CO$_2$-eq) and according to the above it is estimated by the Equation 1.

$$TEWI = [(GWP_r \cdot L_r \cdot n) + (GWP_r \cdot m \cdot (1 - \alpha_{rec}))] + [E_{annual} \cdot \beta \cdot n] \qquad \text{(eq. 1)}$$

The first term of (1) corresponds to the direct emissions potential of the installations due to the eventual release to the atmosphere of the refrigerant gases contained in their circuits. In this term GWP_r is the well-known Global Warming Potential index of the refrigerant gases, which provides the reference for comparing the impact of other greenhouse gases different to CO_2, with independence of its source and/or use once they have been incorporated to the atmosphere. It is evaluated in relative terms to CO_2 radiative effects on the atmosphere for an accepted period of time of 100 years, $GWP_{co_2} = 1$. L_r [kg/yr] is the leakage rate, n [years] is the system operating life, m [kg] the refrigerant charge and α_{rec} [-] the recovery factor, related to the eventual re-use when installations finish their operative life.

In this sense, the refrigerant gases must be chosen not only due to their non-ozone depleting nature, but also to their lower GWP_r values. Some of the presently used gases in conventional compression systems have values of GWP_r that are thousands of times greater than CO_2 (Sarbu and Sebarchievici, 2014). Conversely, other classical refrigerant as Ammonia, R-717, when used both in electrically and/or thermally driven (renewable or not) compression cycles, has the advantage of having a null value of direct emissions potential.

The indirect, the second one, term in expression (1) takes into account the energy consumption E_{annual} [kWh/yr] and the indirect emission factor, β [kg CO_2/kWh], which depends on the primary way in which E_{annual} is obtained, electricity and/or heat. In this work, E_{annual} is related to the energy demand for refrigeration E_{ref} systems by the coefficient of cooling system performance $SCOP$ which here represents the overall efficiency of the conversion of the supplied energy in the effective energy to be removed from the refrigerated space. This efficiency coefficient integrates the well-known parameter COP (Coefficient of Performance), which is related to the operating temperatures, refrigerant gas and cycle configuration, as well as the rest of energy inefficiencies of the other parts and circuits of the cooling system as piping, valves, fans,…

In the case of E_{annual} to be electricity, the calculation of emission factor β_e [kg CO_2/ kWh_e] must account for the energy sources in a particular region, whether renewable or non-renewable, which makes up the corresponding regional energy mix (EEA, 2011). This varies year-on-year for each country although there consensus on using some standard values. For Spain is, β_e= 0.33 [kg CO_2/kWh_e] (IDAE, 2012) or β_e= 0.40±0.26 [kg CO_2/kWh_e] for the UE-27 (EEA, 2011). For the case of using heat as main source of the processes, fossil fuels also have specific values of β as, for example, the natural gas β_{ng}= 0.20 [kg CO_2/kWh_t] (IDAE, 2012).

In cold stores, which are characterized by a well-defined and isolated volume, other well stablished index is Specific Electricity Consumption, SEC [kWh_e/(m^3yr)]. SEC index has, of course a wide variability depending on the size and configuration of the cold stores, the storage temperatures, the location, the product load, the use of energy and the refrigeration load profile, etc. Some reference values are between 14 and 132 kWh_e/(m^3yr) (Mejia, 2008; Prakash and Singh, 2008). In this work a variation of this index has been considered normalizing instead the electricity consumption to the volume of the cold store, the yearly refrigeration energy by processed crops mass or normalized refrigeration load NRL [kWh_{ref}/t] by year.

2.3. Renewable cooling installation

The basic elements of the considered alternative refrigeration system are shown in Figure 3, which are:

- The primary renewable energy source (PES): solar thermal energy, but also heat from biomass.
- Ammonia absorption chiller (AACH). In the thermally driven cooling systems, the energy requested to drive the evaporation/condensation thermo-mechanical cycle of the refrigerant gas is obtained by a sequential absorption/generation process of the refrigerant (adsorbate) gas on a liquid substrate (adsorbent) which is driven by the supply of certain quantity of heat. Although a wide variety adsorbate/adsorbent working pairs have been proposed, the most common are LiBr-H_2O and H_2O-NH_3 (Henning, 2007). In LiBr-H_2O-fed systems, the minimum temperatures in the evaporator are around 5 ºC (Balaras et al., 2007). In H_2O-NH_3 absorption chillers, temperatures in the evaporator are not as limited and can be used for applications below 5 ºC (Balaras et al., 2007), more suitable for industrial applications. Conversely, certain drawbacks must be noted: NH_3 is toxic, the working pressures are higher, and the rectifier needed in the generator outlet causes additional losses. The temperatures required in the generator are between 125 ºC and 170ºC if the absorber and the condenser are cooled by air; and between 80 ºC and 120 ºC if cooled by water, and the COP (single-stage) is between 0.6-0.7 (Balaras et al., 2007). Therefore, these chillers are very suitable to be powered by solar systems with collectors that can efficiently reach temperatures the mentioned temperatures.

- Heat storage (HS) is the storage system that takes care of storing the excess primary energy produced aiming to tackle the nocturnal of low radiation periods. A wide set of options exists, starting from the simplest one, sensible heat in water tanks. More advanced options consist on alternative substances for sensible storage, PCM phase change materials and even the use of thermochemical cycles. As operative alternative, the energy storage in this kind of systems can be also afforded in the form of storing the cold water generated by the chiller (glycolated water solution or brine) Cold Storage (CS).
- Auxiliary heating (AH) is the auxiliary power generation system for activating the chiller. This auxiliary system generally requires a power source to operate i.e. biomass, natural gas, etc.
- Cool distribution system (CD), usually fan coils that are responsible for distributing the cold in the cold room by circulating a fluid at low temperature (glycolated water solution or bine).
- Auxiliary cooling system (AC), which is responsible for removing the necessary energy from the cold room during periods when there is no primary energy source available to activate the chiller.

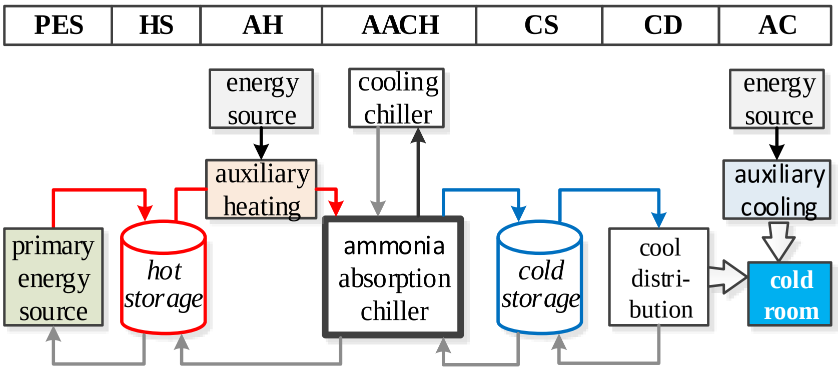

Fig. 3: Cooling systems based on an absorption chiller.

The refrigeration system may contain all the components listed above or only some of them; such as a refrigeration system to exploit a primary energy source, with hot storage and an auxiliary heat system to activate the chiller (PES+HS+AH+AACH+CD); or a refrigeration system to exploit a primary energy source to activate the chiller, with cold storage with support for auxiliary or conventional cooling (PES+AACH+CS+CD+AC).

3. Methods and Calculations

3.1. Refrigeration load estimation

Crops refrigeration chain at the considered case studies is the following (Figure 4): vegetables are received with a temperature T_0 whose value is determined by the ambient temperature in the 5-6 h range prior to receipt, including the transportation, and stored in the pre-refrigeration room in which the temperature reaches T_1=T_0-3 ºC (if, $T_1 \geq T_{preref}$). Then they are categorized, packed, palletised and stored in the refrigeration room which is cooled to the final commercialization temperature T_2 = 8 ºC (Figure 4). The minimum time for the refrigeration process is 18 hours until the product reaches temperature T_2, and this takes into account that the cooling is done by forced air and that the vegetables are packed in boxes and stacked. The weight of the pallets is about 500-700 kg, depending on the product. Some products are reprocessed after being in the refrigeration room, which requires further selection, packaging and palletising due to quality control. This can occur with up to 15% of the production; or they are individually packaged (flow-pack), which can occur in up to 30% of the production. The cooling processes include pre-refrigeration and refrigeration. These are done in cold stores and apply to all products. Refrigeration in the cooling tunnels can be rapid, to speed the refrigeration process.

There are some processes requiring heat for: (1) drying - peppers are washed and subsequently dried in a drying tunnel with forced air heated in a fuel oil boiler, (2) packaging - cucumbers are wrapped individually in a process which requires heat input to shrink the plastic. Certain products such as cucumbers or peppers, that are dried or packed in high-temperature processes, may increase their temperature by 1-2 °C before being introduced into the refrigeration room.

The products remain in the refrigeration room for a maximum of 96 h - between 0-24 h, the product is being cooled; at 48h, 20% of the production has left; at 72 hours, 70% has gone and after 96 h, 100% of the production has gone. On leaving, the pallets are placed in refrigerated trucks for distribution.

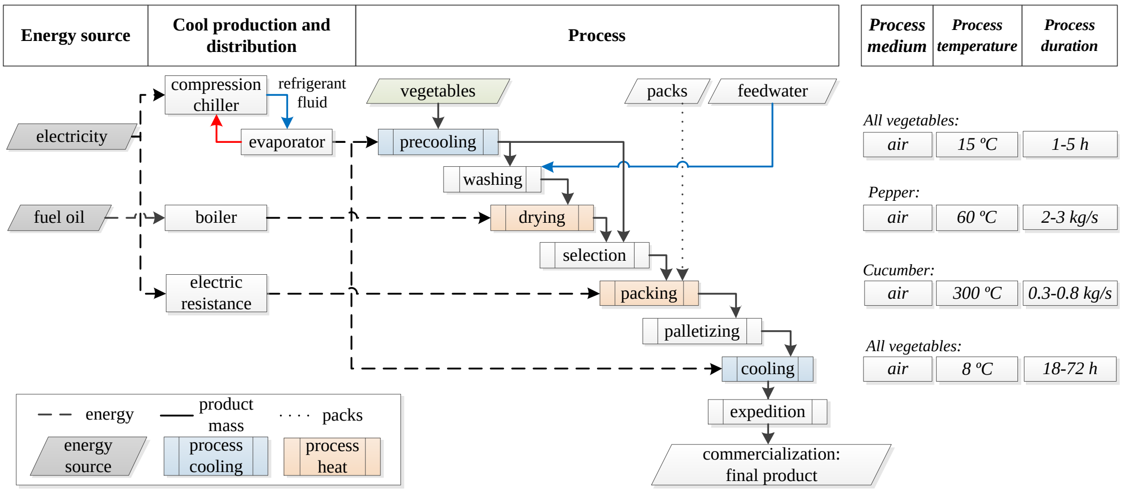

Fig. 4: Diagram of the FVPLC industries process (Case A, initial situation)

The refrigeration load is the energy to be extracted from the cold room to maintain the designed inside temperature. This load coincides with the sum of: 1) the removal of heat (sensible or latent) from a product; 2) the heat transferred by conduction through the surfaces of the room; 3) the radiant heat from outside; 4) the heat transferred by convection from outside (by air infiltration or ventilation), both sensible and latent; 5) the internal heat sources (lights, fan motors, machinery, personnel, etc.); and 6) the heat generated by the product (Trott and Welch, 2000).

A simplified energy balance equation in quasi-steady state, in which the energy gained is equal to the energy lost, can be expressed as:

$$\dot{Q}_{ref} = \dot{Q}_{cc} + \dot{Q}_{ren} + \dot{Q}_p + \dot{Q}_{res} + \dot{Q}_f \qquad \text{(eq. 2)}$$

Where, $\dot{Q}_{ref}$ [W] is the heat that needs to be provided (-) or removed (+) from the cold room; $\dot{Q}_{cc}$ [W] is the heat gained by conduction-convection through the walls, ceiling and floor; $\dot{Q}_{ren}$ [W] is the heat gained by the renewal of inside air and infiltration; $\dot{Q}_p$ [W] is the load needed to refrigerate the product; $\dot{Q}_{res}$ [W] is the load needed for product respiration; and $\dot{Q}_f$ [W] is the input of fans, lights, people and other heat sources. For the cold modelling, we have opted for a simplified dynamic model which takes into account the thermal balance of the chamber. The single zone model makes a heat balance around the chamber by considering the different flows of incoming and outgoing energy:

$$\frac{dT_i}{dt} = \frac{1}{M_{cr}}\left[\dot{Q}_{cc} + \dot{Q}_{ren} + \dot{Q}_p + \dot{Q}_{res} + \dot{Q}_f\right] \qquad \text{(eq. 3)}$$

T_i [ºC] is the temperature; t [s] the time; and M_{cr} [J/ºC] is the thermal mass of the cold room.

Each $\dot{Q}_x$term in (2) and (3) has specific expression that allows estimate $\dot{Q}_{ref}$ (ASHRAE, 2010).

Accordingly, once integrated horyrly resltas the annual energy consumption for vegetable refrigeration in the cold stores, obtained from hourly load figures is 1.934, 1.474 and 2.130 MWh_{ref}/yr (for the three cases studied). Figure 5 shows the summary of the montly, weekly and hourly evolution of this consumption, where we see that the maximum occurs in the period from November to May, (Cases A and B) and in the summer (Case C) because the cooling load is mainly influenced by the amount of manipulated product and the outdoor climate. In Cases A and B, there is less load during the summer months because this period is outside of the normal crop cycles for protected crops in this region.

The refrigeration process load represents 80% of the total, while the remaining 20% is for the pre-refrigeration process. The main refrigeration load is that produced to refrigerate the product,$\dot{Q}_p$, which accounts for about 56-60% depending of the case studied, followed by product respiration loads of 13-17%. The loads for convection and conduction losses represent 10-14%, infiltration loads represent 8-10%, and operating loads, 7%. The refrigeration loads directly depend on the amount of product to be refrigerated and its initial temperature ($R^2 > 0.75$) and fairly related to the difference in temperature between the outer and inner chambers ($R^2 > 0.21$). The annual normalized refrigeration loads are 28,3, 25,7 and 27,9 kWh$_{ref}$/t, respectively, for the studied production cases. For the case of the needs of installed cooling capacity, the maximum cooling power needed to cover 99% of the refrigeration loads are 530, 420 and 540 kW$_{ref}$ (Figure 5) with hourly peak loads of 1.050, 760 and 900 kW$_{ref}$, for the three cases (Figure 6).

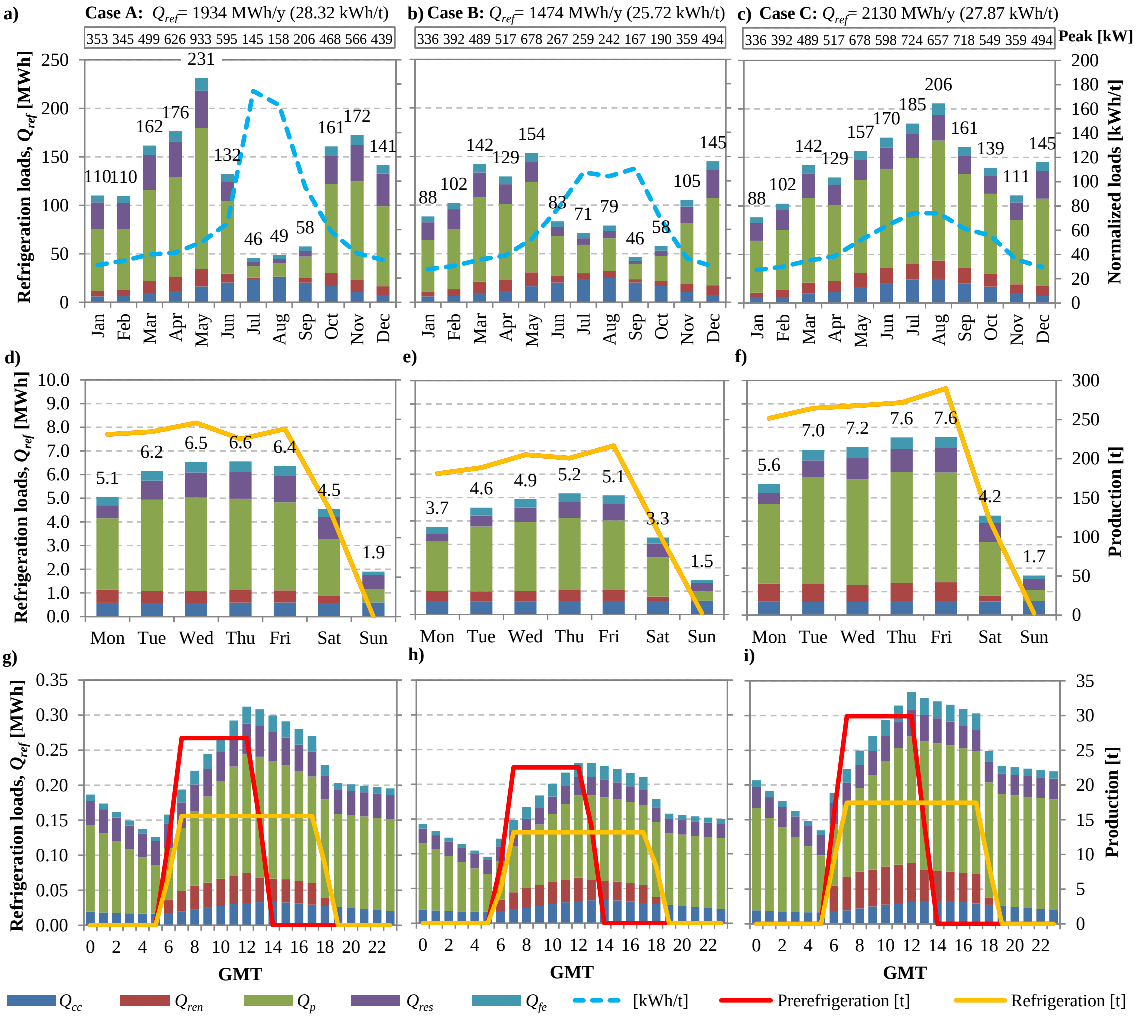

Fig 5: Evolution of the total refrigerated energy consumption of the cases studied, with normalised loads, peak loads as well as annual (a-c), weekly (d-f) and daily (g-i) production.

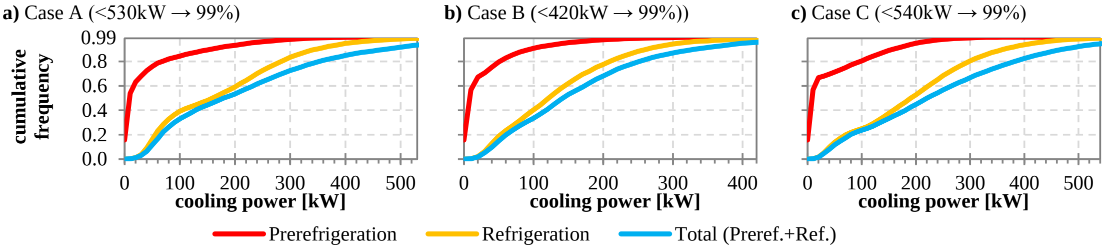

Fig. 6: Cooling capacity of the case studies

3.3 Calculations related to renewable cooling systems

The following scenarios have been defined: the Scenario I (S-I) is a conventional auxiliary cooling system (compression chiller) powered by electricity obtained from conventional sources, the Scenario II corresponds to a cooling system with an ammonia absorption chiller fed with renewable thermal energy. From the refrigeration loads we can obtain the energy consumption required for product refrigeration depending on the equipment used in the different scenario. The electricity consumption associated to refrigeration loads, and their coverage in electrical terms for standard values of $SCOP$of the conventional equipment agrees with as provided by Schweiger et al.,(2011) associated with electricity consumption for refrigeration in the industry 15.3 (NACE Code Rev. 1.1), in Spain.

For the case of the solar thermal installation, a parabolic thought collector (PTC) field has been selected because its higher heat generation capacity and because the availability of specific and modular solutions for industrial processes with certified performance by Solar Keymark. Performance of solar to thermal energy conversion is described by:

$$\eta_{a|G_t} = 0,697\frac{(K_{\theta b}(\theta)\,G_{b,t}+0.133\,G_{d,t})}{G_t} - 0,36\frac{(T_m-T_a)}{G_t} - 0,0011\frac{(T_m-T_a)^2}{G_t} \qquad \text{(eq. 4)}$$

where, T_m [K] is the collector heat transfer fluid temperature, T_a [K] ambient temperature, G_t [W/m^2], $G_{b,t}$ [W/m^2] are $G_{d,t}$ [W/m^2] global, direct and diffuse irradiance at the collector aperture and $K_{\theta b}(\theta)$ [-] is the incidence angle modifier. The solar collector filed provides hot water (t_{cap}=t_{hot}=110ºC) to a single-effect absorption NH_3-water device. Temperature at evaporator is t_{chw}=-3ºC which is transferred to a water solution circulating in chamber fan-coils. Nominal coefficient of performance COP_{nom}=0,60 and the cooling capacity is $\dot{Q}_{cool}$=500 kW$_{\text{cool}}$, fulfilling 98% of the demanded power. As thermal storage medium, hot water has been selected confined in a V_{sto} [m^3] tank having 0,83 W/(m^2 K) thermal losses. It is also considered an auxiliary boiler with a power of $\dot{Q}_{aux}$=900 kW$_{\text{hot}}$.

A model of the system has been elaborated in TRNSYS v17 and the following specific parameters have related (Table2) to estimate system performance for different technical options : 1) overall system efficiency, ε [-], 2) solar fraction, f [-], the percentage of energy produced by the system in regard to the energy demand, that is, *SCOP* weighted refrigeration load, 3) specific solar field area, A_{spec} [m^2/kW$_{\text{cool}}$], input parameter indicating the size of the solar field in regard to cooling capacity of the system and 4) specific storage volume V_{spec} [m^3/ m^2], ratio between storage volume and the size of the solar field.

Tab. 2: Modeled Performance indexes for solar cooling systems

Case	A_{spec} [m^2/kW$_{cool}$]	V_{spec} [m^3/m^2]	Q_{solar} [MWh]	Q_{aux} [MWh]	ε [-]	f [-]
A	0	0	0	2.934	0,00	0,00
	0,5	0	284	2.672	0,45	0,08
	1	0	566	2.473	0,45	0,15
	2	0	1.126	2.186	0,44	0,24
	3	0	1.683	2.018	0,44	0,30
	4	0,2	1.700	1.602	0,45	0,43
	5	0,2	2.825	1.060	0,45	0,61
B	0	0	0	2.377	0,00	0,00
	0,5	0	284	2.113	0,45	0,11
	1	0	565	1.911	0,45	0,19
	2	0	1.124	1.676	0,44	0,29
	3	0	1.679	1.566	0,44	0,34
	4	0,2	1.699	1.058	0,45	0,55
	5	0,2	2.822	595	0,45	0,74
C	0	0	0	3.325	0,00	0,00
	0,5	0	284	3.059	0,45	0,07
	1	0	567	2.834	0,45	0,14
	2	0	1.128	2.498	0,45	0,24
	3	0	1.685	2.300	0,44	0,30
	4	0,2	1.702	1.890	0,45	0,42
	5	0,2	2.829	1.230	0,45	0,61

4. Results and Conclusions

Table 3 summarizes main findings in terms of the selected indexes for the facility level analysis (case A, B and C). In addition to this, as the studied location is included in the zone with higher cooling requirements in all the national systems design guides and regulations, it is possible to assume the obtained normalized load value (NRL = 28.3 kWh_{cool}/t) as a maximum requirement for a more general geographic approach. In this way, the extrapolation to the total fruit and vegetable production in Spain and Andalucía will approach to maximum figures at national and regional levels. CO_2 emissions associated with this consumption, assuming an electricity contribution alone (Scenario I) would be around 84.1 kt CO_2/yr. Using an ammonia absorption chiller powered only by solar energy or biomass, CO_2 emissions would be 77% lower in Scenario II ($F_{S\text{-}B}$=100%) than in Scenario I. In Scenario II, CO_2 emissions would decrease in proportion to the increase in renewable energy contribution.

Tab. 3: Annual energy consumption, primary energy savings and CO2 emissions under different scenarios in the FVPLC industries.

Case		Case A	Case B	Case C	Andalusia	Spain
Refrigeration load, Q_{ref} [MWh_{cool}/yr]		1.934	1.474	2.130	208.900	614.412
Normalized load [kWh_{cool}/t]		28,3	25,7	27,9	28,3 *	28,3 *
Scenario I: (electric chiller)		+ECH+				
Energy consumption, E_{annual} [MWh/yr] (SCOP=2.5)		774	590	852	86.672	254.917
Electrical [MWh_e/yr] (100%)		774	590	852	86.672	254.917
Thermal [MWh_t/yr] (0%)		0	0	0	0	0
SEC: [$kWh_e/(m^3yr)$]		64	49	71		
Scenario II: (absorption chiller)		...+AACH+…				
Energy consumption, E_{annual} [MWh/yr] (SCOP=0.55)		3517	2681	3872	393962	1158712
Electrical [MWh_e/yr] (5%)		176	134	194	19698	57936
Thermal [MWh_t/yr] (95%)		3341	2547	3679	374264	1100777
SEC: [$kWh_e/(m^3yr)$]		15	11	16		
II.($f_{S\text{-}B}$=0%) Solar or Biomass (PES)	*TEWI*: [kt CO_2/yr]	673,6	513,5	741,7	75.458,1	221.935,7
II.($f_{S\text{-}B}$=30%) Solar or Biomass (PES)	*TEWI*: [kt CO_2/yr]	471,5	359,4	519,2	52.822,6	155.360,7
II.($f_{S\text{-}B}$=100%) Solar or Biomass (PES)	*TEWI*: [kt CO_2/yr]	0,1	0,0	0,1	6,5	19,1

In regard to Specific Electricity Consumption (SEC), the obtained values for Scenario I are comparable to those obtained by other authors for similar cold store volumes. Scenario II represents an average savings of 78% in the SEC, produced by the use of AACH. There are variations in the SEC values for the three cases studied mainly due to the different use of the freezers and the load profiles - when their use is more intensive, the SEC is higher - because the product refrigeration load is increased. This variability suggests that the SEC produced an error in the FVPLC industry cases studied. Therefore, the best index to extrapolate to other situations is the normalized load to the amount of refrigerated product.

For the case of the thermal energy to activate the AACH obtained from biomass. FVPLC industries have a close relationship to the crop production area. So, for example, as in case B, with an annual tomato cycle area of 424 has, there is a heat load of 2547 MWh_t/yr (this energy could be covered by the biomass generated from a surface corresponding to 16 -27% of the production area, and 18 -32% for cases A and C (considering a tomato biomass heat output of 3-5 kWh/(m^2yr) and a biomass boiler efficiency of 75%). Solar energy could also be used to cover much of this energy. Figure 7 shows a comparison of the SEC values in the literature and that obtained according analysed scenarios.

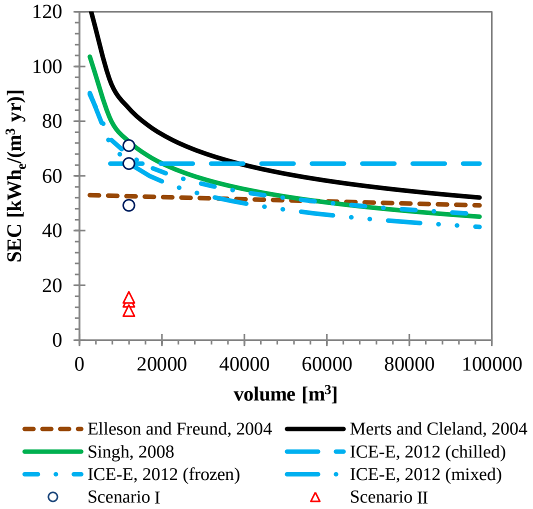

Fig. 7: Analysis of SEC for cases and scenario

An overall economic approach on the basis of the estimated costs in Table 4, elaborated with data compiled in literature and providers, produces an estimated value of levelized cost of energy *LCOE* of 0,07 €/kWhcool for the Scenearío I, which must be considered a low value because the good value of *SCOP* of conventional cooling facilities.

Scenario II presents a less competitive *LCOE* value, especially for those alternative with lower values of *f*. For the more favorable option, case C, in which demand is concentrated in the summer, installations with solar fields in the order of 5 m^2/KWcool and storage of 0,2 m^3/m^2 can reach a value of *LCOE* in the order of 0,08 €/kWhcool in spite of high initial investments and low cooling production performance of absorption chiller in regard to electrical driven compression devices.

Tab. 4: Estimated systems costs for economic analysis

Installation	Concept	Unts [u.]	Costs [€/u.]
Conventional refrigeration system	Compressor/Condenser	P_{cool} [kW]	300
	Evaporator	P_{evap} [kW]	185
Renewable heat driven refrigeration system	Solar field	A_c [m^2]	250
	Storage	V_{sto} [m^3]	$\frac{2496\, V_{sto}{}^{0,67}}{V_{sto}}$
	Chiller NH_3	P_{cool} [KW]	350
	Boiler	P_{aux} [kW]	50
	Fan-coils	P_{fan} [kW]	50
Cooling circuit	Refrigerant	*m* [kg]	10

As overall conclusion, the reduction of environmental impact of refrigeration of fruit and vegetables at FVPLC in Southeastern Spain could be affordable by the use of renewable heat driven absorption machines. The main constrain for the development of these solutions is the high initial investment costs of the devices which, in any case can result in in reasonable values of LCOE, although still higher that no renewable heat.

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6. References

AIRAH, 2012. Methods of calculating Total Equivalent Warming Impact (TEWI), Best Pratice Guidelines. The Australian institute of refrigeration, air conditioning and heating, p. 21.

ASHRAE, 2010. ASHRAE Handbook Refrigeration (SI Edition). American Society of Heating Refrigerating and Air-Conditioning Engineers.

Balaras, C.A., Grossman, G., Henning, H.M., Infante Ferreira, C.A., Podesser, E., Wang, L., Wiemken, E., 2007. Solar air conditioning in Europe-an overview. Renewable and Sustainable Energy Reviews 11, 299-314.

Callejón-Ferre, A.J., Velázquez-Martí, B., López-Martínez, J.A., Manzano-Agugliaro, F., 2011. Greenhouse crop residues: Energy potential and models for the prediction of their higher heating value. Renewable and Sustainable Energy Reviews 15, 948-955.

Coop. agro-alimentarias, 2011. Guidelines for energy efficiency: Fruits and vegetables manufacturing industries. (Manual de ahorro y eficiencia energética del sector. Centrales Hortofrutícolas), Madrid. Spain, p. 50.

EEA European Environmental Agency, 2011. CO_2 (g) per KWh in 2009 (electricity only). European Environment Agengy. https://www.eea.europa.eu/

Elleson, J.S., Freund, S.W., 2004. Benchmarking the energy performance of industrial refrigeration systems. . Interim Draft Report, Industrial Refrigeration Consortium, College of Engineering, University of Wisconsin-Madison, WI.

Fikiin, K., Stankov, B., Evans, J., Maidment, G., Foster, A., Brown, T., Radcliffe, J., Youbi-Idrissi, M., 2017. Refrigerated warehouses as intelligent hubs to integrate renewable energy in industrial food refrigeration and to enhance power grid sustainability, Trends in Food Science & Technology, 60 96-103

Galdeano-Gómez, E., Aznar-Sánchez, J. A., Pérez-Mesa, J. C., Piedra-Muñoz, L., 2017. Exploring Synergies Among Agricultural Sustainability Dimensions: An Empirical Study on Farming System in Almería (Southeast Spain), Ecological Economics 140, 99-109

GRIA, 2013, Register of food industries of Andalusia. (Registro de Industrias Agroalimentarias de Andalucía). Consejería de Agricultura, Pesca y Medio Ambiente (http://www.juntadeandalucia.es/agriculturaypesca/gria/)

IDAE, 2012. Final energy conversion factors - primary energy and CO_2 emission factors - 2011. (Factores de conversión energía final - energía primaria y factores de emisión de CO_2 - 2011). Instituto para la Diversificación y Ahorro de la Energía. Ministerio de Industria, Turismo y Comercio. Gobierno de España.

Sarbu, I., Sebarchievici, C., 2013. Review of solar refrigeration and cooling systems. Energy and Buildings 67, 286-297.

Schweiger, G., Heimrath, R., Falay, B., O'Donovan, K., Nageler, P., Pertschy, R., Engel, G., Streicher, W., Leusbrock, I., 2018. District energy systems: Modelling paradigms and general-purpose tools. Energy 164, 1326-1340.

Schweiger, H., Vannoni, C., Pinedo Páscua, I., Facci, E., Baehrens, D., Koch, M., Pérez, D., Mozetic, L., 2011. Evaluation of the potential of solar thermal energy in the industrial sector. (Evaluación del potencial de la energía solar térmica en el sector industrial), Estudio Técnico PER 2011-2020. IDAE. Instituto para la Diversificacion y Ahorro de la Energía, Madrid, Spain., p. 762.

Swain, M., 2009. Energy use in food refrigeration. Calculations, assumptions and data sources. Food Refrigeration and Process Engineering Research Centre (FRPERC). University of Bristol, Bristol, UK, p. 19.

Torrellas, M., Antón, A., Montero, J.I., 2013. An environmental impact calculator for greenhouse production systems. Journal of Environmental Management 118, 186-195.

Trott, A.R., Welch, T., 2000. 21 - Refrigeration load estimation, Refrigeration and Air Conditioning (Third Edition). Butterworth-Heinemann, Oxford, pp. 214-222.

van der Werf, H.M.G., Garnett, T., Corson, M.S., Hayashi, K., Huisingh, D., Cederberg, C., 2014. Towards eco-efficient agriculture and food systems: theory, praxis and future challenges. Journal of Cleaner Production 73, 1-9.

Wu, X., Hu, S., Mo, S., 2013. Carbon footprint model for evaluating the global warming impact of food transport refrigeration systems. Journal of Cleaner Production 54, 115-124.