Sustainability and Energy Analysis of the Lettuce post-harvest stage by Integration of PV

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***Abstract*—Nowadays, the food sector is improving its energy consumption to achieve a more sustainable industry, and also in economic and environmental terms. Aiming to mitigate global warming and fossil fuel dependence, it is necessary to determine the carbon footprint to assess the main impacts of a typical food production system. Among the different solutions, Life Cycle Assessment is a suitable method to evaluate the environmental impact throughout the entire supply chain. Under that framework, this paper aims to compare the environmental impact of energy consumption in lettuce post-harvest activities using two energy scenarios: current Spanish mix power generation, and sustainable Spanish mix generation by optimizing self-consumption PV power plants and using gate-to-gate LCA. The global warming potential for years and Cumulative Energy Demand are also determined. As a result, we obtained 25.8 gCO$_2$eq and 479.3 kJ/kg; and 17.8 gCO$_2$eq and 398.5 kJ/kg, respectively, for both Spanish generation mix scenarios. Refrigeration energy consumption is the most demanding stage, entailing major emission contributions. PV installations can minimize said impact by 32 % in both impact categories. Further investigation should address the analysis of implementing renewable energy sources in other fresh vegetable supply chain stages, creating a more sustainable food industry.**

Keywords*—*LCA lettuce, GWP and CED, carbon footprint, sustainable

I. INTRODUCTION

According to Evans et al. [1] in the food industry around 50 % of the total energy used in food refrigeration is consumed in retail and commercial refrigeration, and 50 % in cooling, freezing and in warehouse storage. The relationship between environmental sustainability and energy has become essential for enterprises whose main goal is to reduce costs, improving efficiency in energy and material resources use [2]. In 2012, the European Energy Efficiency Directive [3] was published, which aimed to promote more efficient energy use throughout all stages of the energy chain, from production to final consumption. Therefore, agri-food cooperatives must seek alternative ways to optimize energy consumption, improve energy efficiency and contribute to making this sector more sustainable in economic and environmental terms [4]. Indeed, the embedded energy of food consumption by European citizens in 2013 was estimated at 23.6 GJ [5]; this energy can be divided into the different stages of the value chain: agriculture (33.4 %), processing (28.0 %), logistics (9.4 %), packaging (10.7%), use (13.0 %) and end of life (5.5 %).

With regard to energy resources, there is a remarkable dependence on fossil fuels, whilst the share of renewable energy sources remains relatively small (7 %). Consequently, and to contribute to sustainability, it is therefore necessary to estimate the potential environmental damage and resource depletion in terms of environmental sustainability. Under this framework, different authors propose the carbon footprint estimation and cumulative energy demand to assess the main impacts of a food production system [6]. Life Cycle Assessment (LCA) is a method to evaluate the environmental impact throughout the entire supply chain and it enables the comparison of different production systems [7].

The fruit and vegetable LCA by Sim et al. [8] (cradle-to-grave) and tomato ketchup LCA studied by Andersson et al. [9] (cradle-to-retail) provided a significant contribution to post-harvest stages. Nonetheless, a considerable number of authors agree that the field production stage is one of the largest contributors to global warming [10]. Agriculture contributes around 30 % to global greenhouse gas (GHG) emissions [6] and is therefore a significant contributor to climate change [11]. Boschiero et al. studied LCA for apple post-harvest life using two energy scenarios: Italian electric grid mix and renewable mix (88 % of hydropower and 12 % of photovoltaic energy); they obtained 92.2 gCO$_2$eq/kg and 1.7 MJ/kg when the country electric mix was used, and 10.4 gCO$_2$eq/kg and 0.9 MJ/kg with the renewable mix. The impact reduction was 88.8 % for GHG emissions and 44.8 % for energy demand [12]. Girgenti et al. [13] reported the environmental impact of packaged strawberry (cradle-to-grave). For those authors, the energy demand for the cooling process was 6 %; 0.03kWh/kg, and the emission factor for Global Warming Potential for years (GWP) was 0.8g CO$_2$eq/kg. That study proposed a second scenario to reduce the environmental impact by changing packaging materials and using new ones which increase the shelf-life of fruit. Milà i Canals et al. [14] studied the environmental impact of broccoli, salad crops and green beans from cradle-to-grave. Regarding the post-harvest stage, in the broccoli LCA the freezing and packaging (plastic crates and cardboard boxes) were the major contributors. In lettuce, the impact of that stage was negligible, the energy consumption for cooling had a lower impact, and the packaging was not considered in that LCA. By considering that the post-harvest stage currently plays a relevant role in energy consumption and, according to the specific literature, only few works have focused on improving sustainability at that specific stage.

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This work aims to analyze the energy consumption and environmental impact of the lettuce post-harvest to identify which stages represent a major environmental impact, proposing preliminary sustainable options. The South of Spain has optimal climate conditions for growing vegetables. The Region of Murcia for instance, leads lettuce production. About 35,000 hectares of lettuce are grown in Spain, 16,000 hectares of which are in the Region of Murcia [20]. In 2019, 68 % of the lettuce exported by Spain were from that region and in 2018 Spain was the world's foremost exporter [21]. Therefore, the location of our industry case study details one of the most important areas for lettuce growing in Spain.

The rest of the paper is structured as follows. Section II discusses goal and system boundaries; Section III presents the life cycle inventory; Section IV the results and discussion and finally, Section V gives the conclusions.

II. GOAL AND SYSTEM BOUNDARIES

This study aims to compare the energy environmental impact in lettuce post-harvest activities under two generation mix scenarios: current country mix generation and an electric mix generation combined with PV power plants. The case study is located in Spain, and the country is then selected by considering its relevant share of renewables. ISO 14040-14044 [14,15] were used to structure this work and arable and vegetable crops UN CPC 012 guidelines [17] were used to select the functional unit (FU), which is defined as 1 kg of fresh lettuce. Gate-to-gate lettuce LCA is considered in this performance analysis. The authors only include the energy required by machinery, since the lettuce is received in the warehouse until it is ready to be transported to retailers. Figure 1 shows a general overview of the global process and the stages analyzed in this work. As can be seen, after lettuce is harvested and packed in the field, it is transported to the warehouse.

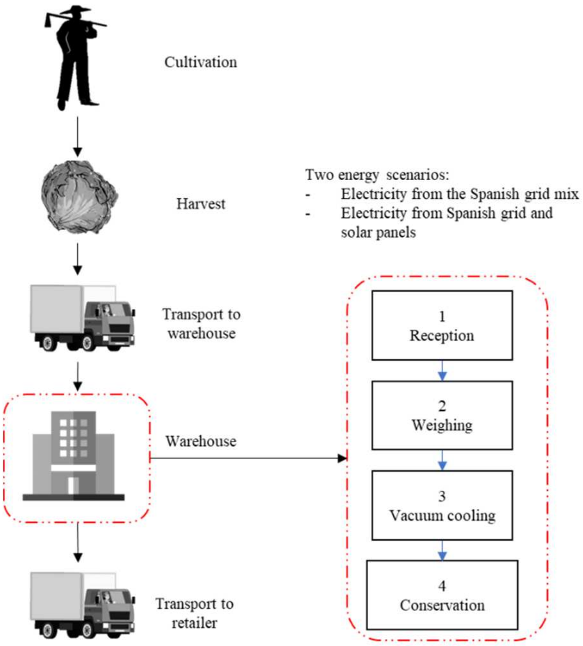

Figure 1. System boundaries of the analyzed production cycle. The left part shows the system from cultivation to transport to the retailer. The right part shows in detail the post-harvest stages performed in the warehouse.

The staff then unload the pallets and weigh the lettuce using forklifts and an electric pallet truck. Subsequently, it is cooled by vacuum equipment, and the temperature falls to 4°C in 20 min. After this process, the lettuce is refrigerated in cold chambers at 2ºC for 48 h until final shipping.

The Spanish industry in this case produces and handles several vegetables products. For this reason, a mass allocation is assumed to establish the energy requirements of fresh lettuce in post-harvest activities. Table I shows the list of vegetables with the mean percentage during lettuce post-harvest. The economic allocation has not been chosen since the economic value of these products is very similar and does not vary significantly.

III. LIFE CYCLE INVENTORY

The energy data of the machinery is determined from an energy declaration ISO 50001. This International Standard specifies the requirements to establish, implement, maintain, and improve an energy management system. It also allows an organization to have a systematic approach to achieve continuous improvement in its energy performance, including energy efficiency, the use, and consumption of energy [18]. This report also contains the number of machines, rate power (kW), and their average annual use (h/year). In this way, the energy consumption for lettuce post-harvest stage can be calculated. Table II summarizes the total energy requirements over the year and per functional unit. The equipment with the highest energy requirements is the cooling compressor and vacuum cooling. The refrigeration process demands a remarkable amount of energy to achieve and maintain the set-point temperature. Nevertheless, and comparing vacuum cooling with other technologies such as air cooling and hydrocooling, vacuum cooling has the lowest energy cost per unit of cooled product [19]. The lowest energy consumption values are for scrubber and strapping machines.

TABLE I. LIST OF VEGETABLES AND THE MEAN PERCENTAGE IN MASS DURING LETTUCE POST-HARVEST

Vegetables	Mass allocation
Iceberg lettuce	56.0 %
Cauliflower	24.0 %
Broccoli	8.0 %
Melon	6.0 %
Cabbages	3.0 %
Other lettuce varieties	3.0 %

TABLE II. LIFE CYCLE INVENTORY IN LETTUCE POST-HARVEST ACTIVITIES

Equipment	**Inputs**	
	Kwh (Year)	***kWh/FU***
Light	86,456	7.8
Electric pallet truck	255,88	0.6
Forklifts	6,997	2.3
Batteries	11,315	1.0
Weighing machine	6,035	0.5
Box making machine	45,261	4.1
Strapping machine	6,052	0.5
Scrubber	3,621	0.3
Vacuum cooling	114,579	10.3
Refrigerated chamber	12,400	1.1
Cooling compressor	252,346	22.6

As previously commented, the LCA is assessed by considering two generation mix scenarios: (*i*) the Spanish electricity power mix generation (SpMix); and *(ii)* the Spanish mix generation combining with PV power plant installations located on the roof of the industrial warehouse case study (SpMix+PV). Both power generation scenarios are described in Table III, including different energy sources and their corresponding emission factors for each impact category. The Spanish industry case also provided the hourly energy curves. It allowed us to calculate the maximum PV energy that said renewable installation can produce under Spanish self-consumption requirements. As a result, we obtained that around 35 % of the total electricity energy demanded by this industry can be supplied by this renewable resource due to solar availability; 1,630 m^2 of photovoltaic panel will be necessary to supply 35 % of the total energy demand in lettuce post-harvest. The software used for LCA assessment was SimaPro version 9.1.1 [19] and the methods used were Cumulative Energy Demand (CED) [20] and the Global Warming Potential for 100 years (GWP) [21].

"Electricity, high voltage {ES} market for| APOS, U" was updated to create the Spanish electric mix in 2020 with percentages reported in the Spanish electrical network [22], this indicator covers: electricity inputs produced in the country and from imports, transmission network, direct emissions to air and electricity losses during transmission. "Electricity, low voltage {ES} electricity production, photovoltaic,3kWp slanted-roof installation, single-Si, panel, mounted, APOS, U" has been chosen for photovoltaic electricity. This indicator covers the production of grid-connected low voltage electricity with a 3kWp building integrated photovoltaic module, installation on slanted roof and inverter to convert the low voltage direct current (DC) power into alternating current (AC) power, and includes the tap water used for cleaning and its treatment. The disposal scenario of the photovoltaic panel is not included in the study.

IV. RESULTS AND DISCUSSION

Figure 2 shows the results of Global Warming Potential for the two energy scenarios: 25.8 gCO_2eq for SpMix, and 17.8 gCO_2eq for SpMix+PV.

TABLE III. PERCENTAGE OF ELECTRICITY SOURCES INVOLVED IN THE TWO ELECTRICITY PRODUCTION OPTIONS

Electricity scenario		
Electric mix sources (%)	***SpMix***	***SpMix+PV***
Nuclear	22.0	14.3
Wind	22.0	14.3
Combined cycle	18.0	11.7
Hydraulic	12.0	7.8
Cogeneration	11.0	7.2
Solar	8.0	40.2
Coal	2.0	1.3
Fuel and Gas	2.0	1.3
Other renewable	3.0	1.9
Energy and emission factor		
kgCO_2eq/kWh	0.50	0.35
MJ/kWh	9.40	7.80

When the PV power plant is considered for simulations, CO_2eq emissions are reduced by 32 %. The principal compounds mostly contributing to global warming are the following: carbon dioxide (CO_2), dinitrogen monoxide (N_2O), CFC-114, and methane (CH_4). Regarding the contribution of the global process, the energy resources that increase CO_2eq emissions are coal, lignite, and natural gas, i.e., the non-renewable energy sources.

Figure 3 shows the Cumulative Energy Demand for the two corresponding different scenarios. The total Cumulative Energy Demand (CED) accounts for 479.3 kJ/kg for SpMix, and 398.5 kJ/kg for SpMix+PV. When SpMix+PV is considered, the energy embedded is lower. This is due to the renewable energy technologies requiring low energy input to obtain electric power and, consequently, the environmental impact is considerably lower [23]. The main contribution in Global Warming Potential and Cumulative Energy Demand is the cooling phase which covers energy demand of the cooling compressor (44 %), vacuum cooling (20 %) and the refrigeration maintenance (2 %). The second activity with a high contribution is lighting (15 %) whilst the third activity is due to loading and uploading pallets (8%) which covers the electricity consumption of pallet truck, forklifts and batteries, and by energy consumption in assembling cardboard boxes (8 %).

Figure 4 depicts CED values divided by non-renewable and renewable sources for both the SpMix and the SpMix + PV scenarios. It should be noted that by increasing the percentage of PV energy, the global energy consumption values are lower for each type of energy source.

With the aim of estimating the background of the impacts on each type of source, we analyzed their specific contribution in the process. Indeed, the use of coal, natural gas, and crude oil enhance the impacts on non-renewable fossil fuel sources. Regarding nuclear energy, uranium is the main component, and for non-renewable biomass it is due to primary forest and arable land. The gross calorific value of primary forest biomass is the main contributor for the biomass resource. Among the different renewable energy resources currently available to be integrated into the different sectors, such as wind, solar, geothermal…, the Spanish power system impact is mainly due to the wind resource accounting for 22 % in SpMix.

V. CONCLUSIONS

This paper compares the environmental impact of energy consumption in lettuce post-harvest activities by using two energy scenarios: the current Spanish mix power generation and a sustainable Spanish mix generation by optimizing self-consumption PV power plants and using gate-to-gate LCA. In this work, we demonstrate that lettuce post-harvest refrigeration is the stage involving major contributions to global warming potential, 68 % of greenhouse gases are released during that stage. All equipment used for these post-harvesting processes is currently very energy demanding. Among them, the main impact consumptions are the cooling compressor (44 %) and the vacuum cooling (20 %). By considering the relevant solar resource available in the Spanish case study, the integration of PV power plant installations under self-consumption mode can reduce the energy demand and the greenhouse gas emissions by 32 %.

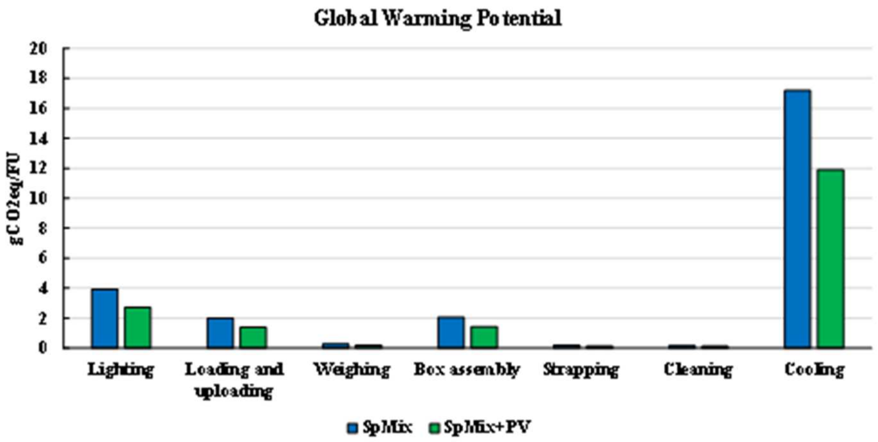

Figure 2. Global warming emission factor for Spanish electric mix (SpMix) and SpMix with photovoltaic panels (SpMix).

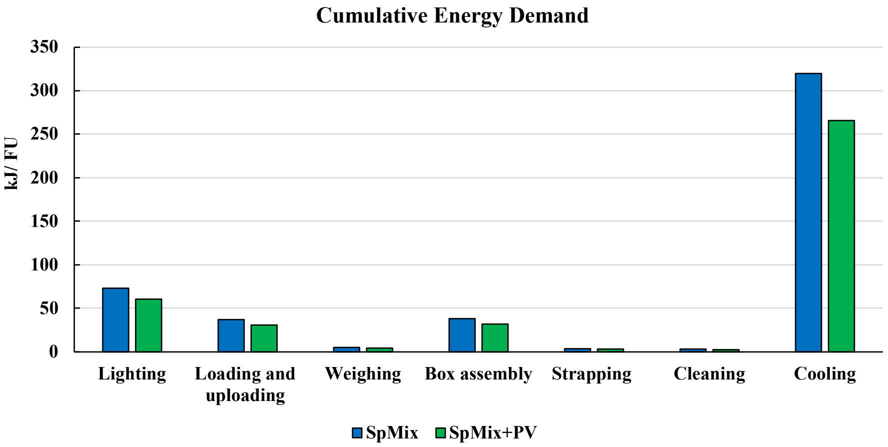

Figure 3. Cumulative energy demand for Spanish electric mix (SpMix) and SpMix with photovoltaic panels (SpMix).

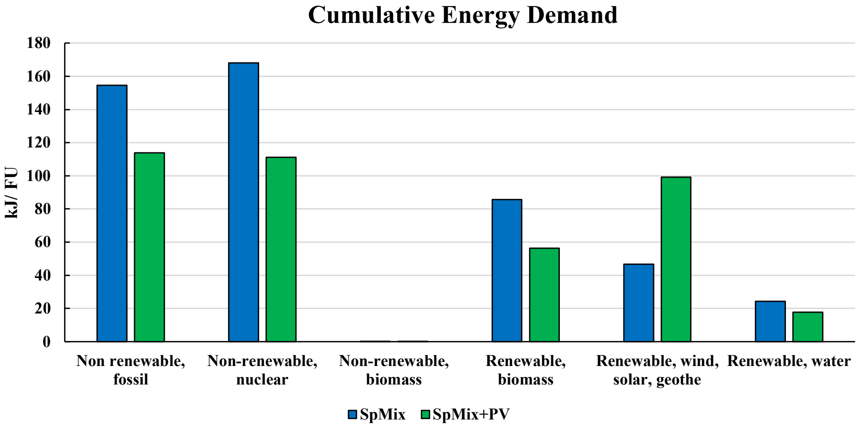

Figure 4. Cumulative Energy Demand divided by non-renewable and renewable sources: SpMix and SpMix + PV scenarios.

Further research must include the implementation of PV installations in other stages of the fresh vegetable supply chain, leading to a more sustainable food industry. As has been observed, the impact on climate change and CED has similar behavior. Therefore, for further investigation in the comparison between the SpMix and SpMix+PV it would be necessary to assess other impact categories such as ozone layer depletion, acidification, eutrophication, and human and environmental toxicity.

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