Energy cost impact analysis on the total cost of the crop production for different operating conditions. A salad production case study

Alice Arcasi[a], Alfonso William Mauro[a], Giovanni Napoli[a] and Antonio Marco Pantaleo[b]*

[a] *Department of Industrial Engineering, Federico II University of Naples, Naples, Italy,*
Corresponding author e-mail: wmauro@unina.it
[b] *Department of Agro-Environmental Sciences, Aldo Moro University of Bari, Bari, Italy*

Abstract:

Nowadays, with the constant global population growth, urbanization, pests use, climate change and resource degradation, the water-energy-food link is constantly stretched. In order to achieve water and food security, sustainable agriculture and energy production, the efforts of the next few years will be aimed to correctly balance these aspects. Therefore, it will be necessary both to improve the energy performance of traditional systems in the agricultural sector and at the same time to develop alternative and innovative ones. In this context, data from a local farm producing salad have been processed in order to relate the energy consumption of each processing phase to the produced kilogram of crop. In particular, thermal loads are attributed to the corresponding primary energy consumption. A thermo-economic analysis was carried out by considering different scenarios in terms of external ambient temperature and specific cost of electricity. Results show that the thermal load exchanged with the external ambient through the walls and the roof of the plant is about the 20% of the outgoing thermal load of the evaporator during the lighting hours whereas the thermal load of the auxiliaries (including the production lines) is about its 80%. Moreover, the variation of both the fourth range production lines operating time and the external daily temperature causes a variation in the total energy consumption related to the kilogram of processed product – up to 128%. Finally, several economic scenarios have been implemented in order to take into account the variation of the specific cost of electricity.

Keywords:

Thermo-economic analysis; Salad production.

1. Introduction

1.1. Context

Nowadays, with the constant global population growth, urbanization, pests use, climate change, resource degradation and scarcity, the water-energy-food link is constantly stretched and heavily tested. Particularly, serious and different problems affect the agricultural sector. First of all, the huge water usage accounts for 70% of the total global freshwater withdrawals [1] and it is expected that it will increase about 55% by 2050 [2]. In addition, energy consumption in the agricultural sector accounts for 3% in the European scenario and for 2% in the Italian one, respectively [3]. Moreover, the energy demand will increase about 3 times by 2050 worldwide [4]. On the other hand, it is estimated that the global population will reach 9.8 billion by 2050 and 11.2 billion by 2100 [5] in a non-uniform way worldwide. Additionally, the intense urbanization will affect more than 70% of world population. All these aspects will contribute to an intensification in the food production sector about the 60% by 2050 – it is worth noting that this sector accounts for 30% of the global energy consumption including also the cold chain and the transport sector. This scenario is exacerbated by the scarcity of arable land as well as the huge use of pesticides and chemical substances: in fact, about 1.9 Mtons of them have been employed in agricultural sector during 2019 in the EU context [6][7]. In order to achieve water and food security and at the same time sustainable agriculture and energy production, the efforts of the next few years will be aimed both to improve the energy performance of traditional systems of the agricultural sector (i.e. open fields and greenhouse systems) and at the same time to develop alternative and innovative ones by considering the ongoing energy transition – such as the indoor farming method.

As a matter of fact, several issues affect the traditional farming methods: their productivity is in fact strongly dependent on the exterior climate conditions, and they need an artificial lighting system and involve a high amount of water if greenhouse systems are installed in cold regions or hot/warm ones respectively, especially if compared to the ones of innovative and alternative agrifood systems such as vertical farms [8][9][10][11].

https://doi.org/10.52202/069564-0236

For the best of authors' knowledge, literature about the modelling of post cultivation phases of greenhouse systems is poor. Stanghellini et al [12] developed a model for the evaluation of evapotranspiration rate load of the plants by considering a greenhouse such it is considered one of the main energy load of those systems. The model includes the effect of the multilayers of the crop and the solar radiation is empirically evaluated as well as a careful calibration of the main parameters of interest is needed. Righini et al [13] developed and validated a greenhouse climate-crop yield model in order to correct manage those systems at high latitudes. Results show that the model is able to predict the air temperature with a very good agreement, with a relative root mean square error lower than 10%. A model for the energy optimization of greenhouses was developed by Weidner et al [14] for different climate zones in order to optimize the interior climate conditions and consequently productivity of the systems. From the abovementioned issues and lacks in literature, it is clear that in a context of energy transition regarding all the sectors and production processes, it is important to correctly model the post cultivation processes of traditional greenhouse systems in order to evaluate their energy consumption and relate it to the kilogram of processed product. The main purpose of this approach is to minimize their energy consumption as well as costs and at the same time maximize their productivity. In fact, from an economic and entrepreneurial point of view it is very useful to quantify both the rate of cost for electricity for the processed kilogram of product and the one for different scenarios by varying economic parameters (such as the specific cost of electricity) and those related to the performance of production lines, facilities and environmental conditions.

1.2. Objectives of the work

In this context the main goal of the manuscript is to model traditional agrifood system taking into account all the parameters of interest, such as external conditions, internal ones, crop type production, air conditioning and lighting systems and cost analysis. The modelling purpose is to relate the energy consumption of all the processing phases to the produced kilogram of product in order to maximize its productivity while minimizing its energy consumption and consequently its costs. In detail, data from a local farm producing salad have been processed and a thermo-economic analysis was carried out by considering different scenarios in terms of external ambient temperature and specific cost of electricity. Specifically, it is worth noting that the processing phases taken into account for the analysis are the post cultivation ones up to the final product picking for the shipping: consequently, both water and energy consumption concerning the raw materials cultivation phase are neglected.

2. Method

In order to relate the energy consumption of each processing phase (from post cultivation to final product) to the kilogram of final product intended for the market, it is fundamental to correctly evaluate all the energetic loads involved in the analysis. With this aim, in this section the implemented methodology is explained. The whole farm plant in which the entire production process takes place is reported in Figure 1 in which all the potentially thermal loads are considered.

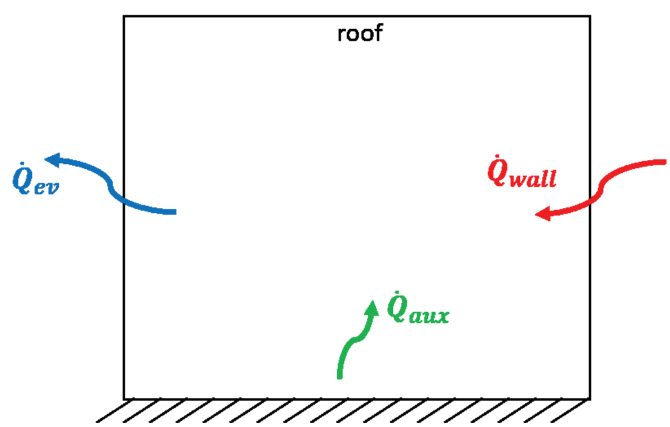


Figure 1 *- Plant schematization with the potentially energetic loads.*

In Figure 1 $\dot{Q}_{wall}$ is the thermal load exchanged with the external ambient through the walls and the roof of the plant, $\dot{Q}_{aux}$ is the thermal load caused by the auxiliaries (pumps, fans, lighting system, ecc) and the production lines; finally, $\dot{Q}_{ev}$ is the outgoing thermal load of the evaporator. It is clear that, from an energetic balance to the control volume reported in Figure 1, the sum of the thermal load exchanged with the external ambient

https://doi.org/10.52202/069564-0236

through the walls and the roof and the one caused by auxiliaries is counterbalanced by the outgoing thermal load of the evaporator:

$$\dot{Q}_{ev} = \dot{Q}_{tot} = \dot{Q}_{wall} + \dot{Q}_{aux} \tag{1}$$

In the energetic analysis the latent power due to the staff presence in the plant during the product's processing phases has been omitted as it is significantly lower compared to the previous ones as well as difficult to estimate. In order to evaluate the thermal load $\dot{Q}_{wall}$ through the walls and the roof of the plant it is useful to refer the analysis to the generic j-th cell in which a specific processing phase takes place as shown in **Figure 2** with both the plan and the section views reported:

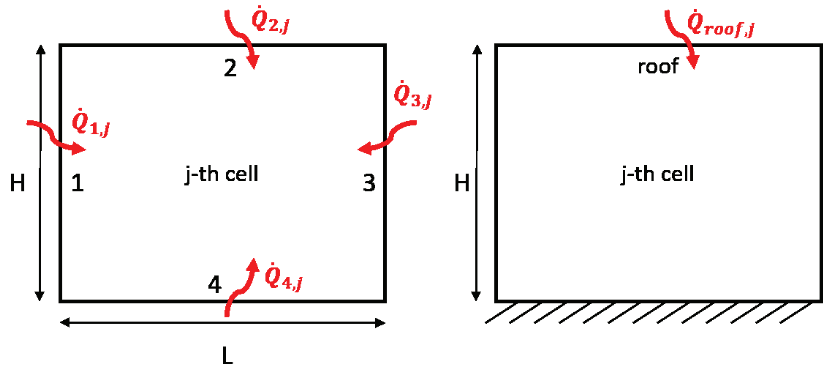


Figure 2 *- Plan and sectional view of the generic j-th cell with the indication of the thermal loads exchanged through the walls and the roof.*

The analysis was carried out by assuming that the internal temperature of the cell for the related processing phase is fixed to be T_j and by associating to each processing phase of the product a specific cell of the plant. Moreover, the whole plant is served by a refrigeration unit. The thermal load related to the j-th processing phase is defined as the sum of the thermal loads exchanged through the walls and the roof as reported in equation (1):

$$\dot{Q}_{cell,j} = \dot{Q}_{1,j} + \dot{Q}_{2,j} + \dot{Q}_{3,j} + \dot{Q}_{4,j} + \dot{Q}_{roof,j} \tag{2}$$

Thermal loads of the walls and the roof are evaluated taking into account the radiative, convective and conductive contributes to the heat transfer mechanism and they are reported in the follow equations:

$$\dot{Q}_{1,j} = \dot{Q}_{wall,1} = \dot{Q}_{c,int} \tag{3}$$

$$\dot{Q}_{k} = \dot{Q}_{c,int} \tag{4}$$

$$\dot{Q}_{rad} = GAa \cdot cos\vartheta \tag{5}$$

$$\dot{Q}_{c,ext} = h_{ext}A\left(T_{amb} - T_{wall,ext}\right) \tag{6}$$

$$\dot{Q}_{c,int} = h_{int}A\left(T_{wall,int} - T_j\right) \tag{7}$$

In the previous equations, A is the surface area, G is the solar radiation, ϑ is the angle of incidence of the solar radiation, h_{ext} is the external convective heat transfer coefficient, h_{int} is the internal convective heat transfer coefficient, $T_{wall,int}$ and $T_{wall,ext}$ are the internal and the external wall temperature respectively and a is the absorption coefficient. Therefore, the thermal load of the generic j-th cell $\dot{Q}_{cell,j}$ can be considered as the sum of the thermal power exchanged through the walls and the roof. Finally, the total thermal power of the considered plant $\dot{Q}_{wall}$ will be calculated as the sum of the thermal power of each cell. In detail, the total thermal power of the whole farm has been evaluated during the year by considering Naples' hourly temperature profile. Moreover, by knowing the quantity of product treated during the specific processing phase j-th (m_p^j) and its residence time inside the generic j-th cell $\left(\Delta\vartheta_j\right)$, the energy consumption of the j-th process will be evaluated and referred to the produced kilogram of raw material:

$$E_{raw\ mat.,j} = \left[\sum_{i=1}^{N_{step}} \left(\frac{\dot{Q}_{cell,j}(T_{amb,i}) + \dot{Q}_{aux,j}}{\dot{Q}_{tot}} \cdot \dot{L}_{comp,i} + \dot{L}_{aux,p,j,i} \right) \right] \Delta\vartheta_j \cdot \frac{1}{m_p^j} \tag{8}$$

In Equation (8) $\dot{Q}_{aux,j}$ is the thermal load caused by the auxiliaries (pumps, fans, lighting system, ecc) and the production lines during the j-th processing phase, $\dot{L}_{aux,p,i}$ is the mechanical power of auxiliaries (pumps, fans, lighting system, ecc) and the production lines of the considered processing phase whereas $\dot{L}_{comp,i}$ is the mechanical power of the compressor of the refrigeration unit serving the plant and $\dot{Q}_{tot}$ is the one defined in the previous Equation (1). Finally, N_{step} is the ratio between the time of the j-th process and the chosen time step. The energy consumption of the whole process for the considered raw material is the sum of the energy consumption of the j-th phases and, in order to evaluate the rate of cost for electricity – that will be defined as RCE – per kilogram of processed product, the total energy consumption of the M processes is then multiplied by the specific cost of electricity as reported in Equation (9):

$$RCE = \left(\sum_{j=1}^{M} E_{raw\ mat.,j} \right) \cdot specific\ cost\ of\ electricity \tag{9}$$

The considered case study is referred to the production of salad of a local farm and the analysis was carried out in order to include different scenarios in terms of external ambient temperature and specific cost of electricity by following the presented methodology.

3. Case study

For the present study data from a local farm near Naples have been processed in order to evaluate the rate of cost for electricity and relate it to the produced kilogram of product (salad). The identified processing phases are reported in Figure 3 in the relative flowchart:

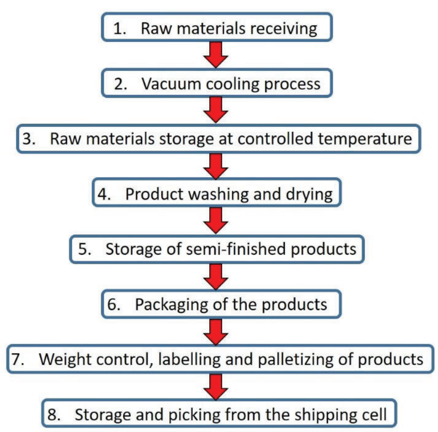


***Figure 3** – Processing phases for the energy consumption analysis.*

In detail, the raw materials, previously grown in traditional greenhouse systems, arrive in the first cell (defined as cell 1); then the cooling process takes place and subsequently the raw materials are stored in the cell number 3. In the 4th cell both washing and drying processes occur and the semi-finished products are stored in the 5th cell from which they are bring to the cell number 6 for the subsequent phase of packaging. Finally, the products' weight control, labelling and palletizing occur in the 7th cell and then the final product is stored in the 8th cell from which it is picked for the shipping. In Table 1 the one-to-one correspondence between the specific processing phase and the nomenclature is reported:

https://doi.org/10.52202/069564-0236

__Table 1__ - Nomenclature and relative area of the processing phases.

Cell	*Processing phase*	$A\ [m^2]$
1	Raw materials receiving	1300
2	Vacuum cooling	310
3	Raw materials storage	2200
4	Product washing and drying	300
5	Storage of semi-finished products	450
6	Packaging of the products	750
7	Weight control, labelling and palletizing	1600
8	Storage and picking from the shipping cell	30

3.1. Operating conditions

Operating conditions of the farm in terms of quantity of product treated during the specific j-th processing phase m_p^j and its residence time inside the generic j-th cell $\Delta\vartheta_j$ as well as data about the refrigeration unit serving the whole plant and production lines with their on/off times have been processed and the rate of cost for electricity related to the processed kilogram of product was estimated. In detail, the analysis was carried out by considering several daily temperature profiles from January 9, 2023 to January 13, 2023. The thermal load $\dot{Q}_{wall}$ through the walls and the roof of the plant has been calculated by considering 0.1 as the absorption coefficient a and the value of the insulating material's thermal conductivity k has been fixed to $0.023\ W/mK$. As regard the thermal load caused by the auxiliaries $\dot{Q}_{aux}$, the first range production lines have been assumed all in operation from 4am to 8pm, whereas for the fourth range production lines data provided by the monitoring of the farm have been considered. Finally, data about the outgoing thermal load of the evaporator $\dot{Q}_{ev}$ during the second week of January 2023 have been taken into account from the monitoring of the local farm. Details about the operating conditions in which the analysis was carried out are reported in Table 2:

__Table 2__ - Operating conditions for the thermo-economic analysis.

Month	*Day*	$\dot{Q}_{wall}$	*First range production lines operating hours*	*Fourth range production lines operating hours*
January	9	$k = 0.023\ W/mK$ $a = 0.1$	16h	19h 30'
	10			16h
	11			17h
	12			16h 30'
	13			16h 30'

3.2. Thermal loads evaluation

In the operating conditions above described, all the thermal loads of interest – $\dot{Q}_{wall}$, $\dot{Q}_{aux}$ and $\dot{Q}_{ev}$ – have been calculated following the methodology presented in the previous section. Shown below the hourly dimensionless results of the thermal loads for the second week of January 2023, for the operating conditions reported in Table 2. It is worth noting that all the data shown in Figure 4(a)-(e) have been dimensionless with respect to the maximum value of the outgoing thermal load of the evaporator:

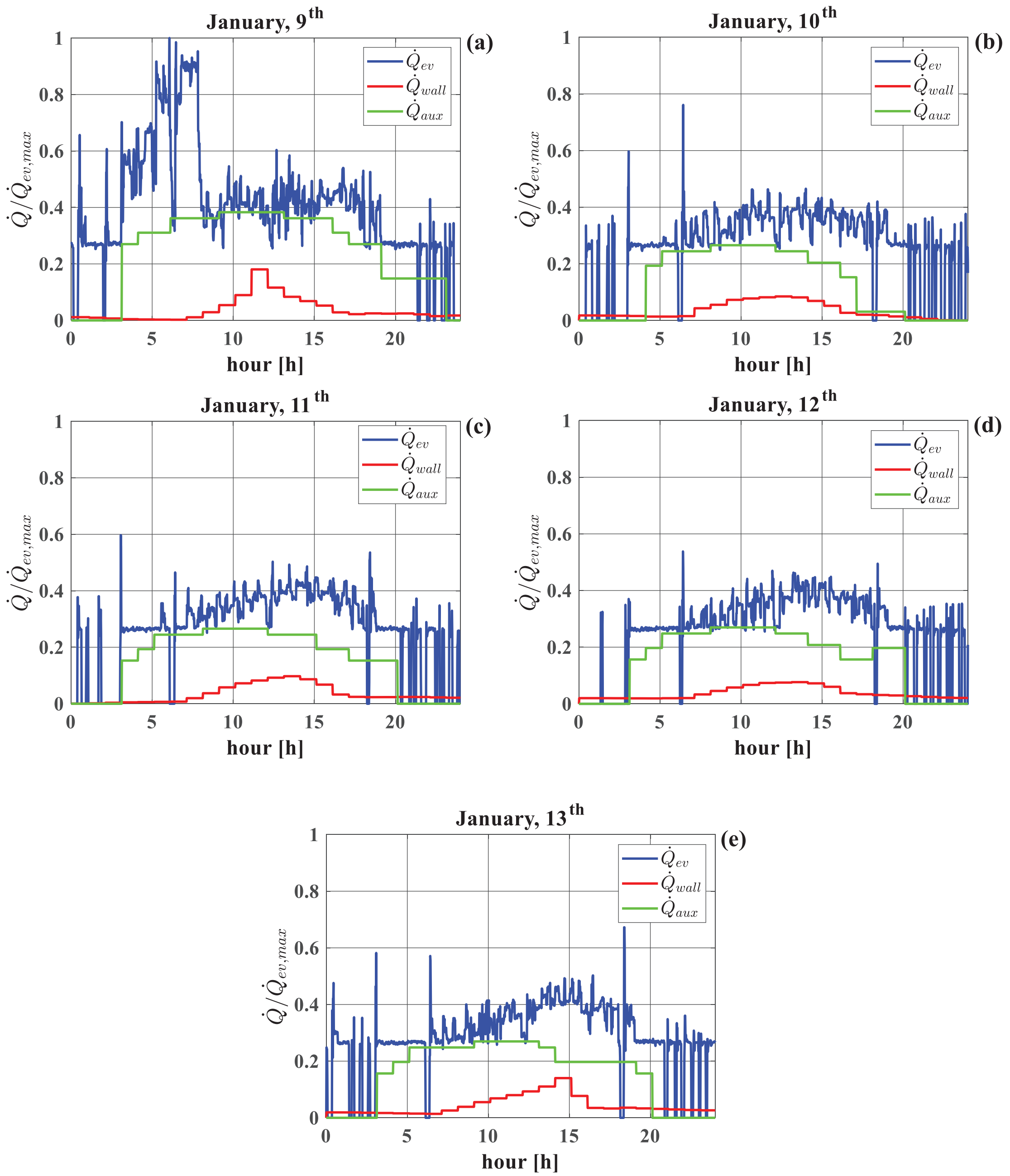


Figure 4 *- Hourly dimensionless thermal loads evaluation for the second week of January, 2023 in the operating conditions reported in Table 2. (a) January, 9th. (b) January, 10th. (c) January, 11th. (d) January, 12th. (e) January, 13th.*

It can be seen that the sum of the thermal load caused by the auxiliaries $\dot{Q}_{aux}$ and the one exchanged through the walls and the roof the plant $\dot{Q}_{wall}$ is continually counterbalanced by the outgoing thermal load of the evaporator. In detail, the thermal load exchanged with the external ambient through the walls and the roof of the plant is, at most, about the 20% of the outgoing thermal load of the evaporator during the lighting hours whereas the thermal load of the auxiliaries (pumps, fans, lighting system, ecc) and the production lines is about the 80% of it. This trend occurs for all the operating conditions considered and for all the days taken into account in the energetic analysis.

https://doi.org/10.52202/069564-0236

4. Results and discussion

4.1. Evaluation of the energy consumption related to the kilogram of product

Once the thermal loads of interest have been evaluated in the operating conditions reported in Table 2, the energy consumption related to the kilogram of processed product (salad) of each processing phase has been calculated by following Equation (8) for the second week of January. Data related to the quantity of product treated during the specific processing phase j-th (m_p^j) and its residence time inside the generic j-th cell $\left(\Delta\vartheta_j\right)$ have been taken into account from the monitoring of the local farm. Then, the total daily energy consumption related to the kilogram of processed product has been considered as the sum of the specific energy of each processing phase by following Equation (9). In Table 3 results in terms of total daily energy consumption related to the kilogram of processed product are reported:

Table 3 *- Daily energy consumption related to the kilogram of processed product during the second week of January.*

Month	*Day*	$\left(\sum_{j=1}^{M} E_{raw\ mat.,j}\right)\left[\frac{kWh}{kg}\right]$
January	9	4.46
	10	2.52
	11	2.37
	12	1.96
	13	2.36

It can be noted that the total energy consumption of January, 9th is significantly higher compared to the others daily total energy consumption: $+77\%$ and $+128\%$ compared to the ones of January, 10th and 12th, respectively. This trend is caused by the higher thermal load of the auxiliaries $\dot{Q}_{aux}$ during the operating hours of the farm due to the higher operating time of the fourth range production lines. It is worth noting that the energy consumption related to the kilogram of processed product shown in Table 3 is strongly dependent on the performance of the production lines, on their operating times and finally on the external conditions. Therefore values in Table 3 have not to be considered as reference ones, but they can allow to consider and compare different solutions and scenarios able to reduce the rate of cost for electricity for kilogram of processed product for the presented case study.

4.1. Economic analysis

Finally, once the thermodynamic analysis has been completed, an economic one was implemented by following Equation (9). In detail, the specific cost of electricity has been fixed to $0.22\ €/kWh$ [15] – the cost is referred to the average price during the whole year 2022 – and the daily rate of cost for electricity (RCE) related to the kilogram of processed product has been calculated for the second week of January, as shown in Figure 5.

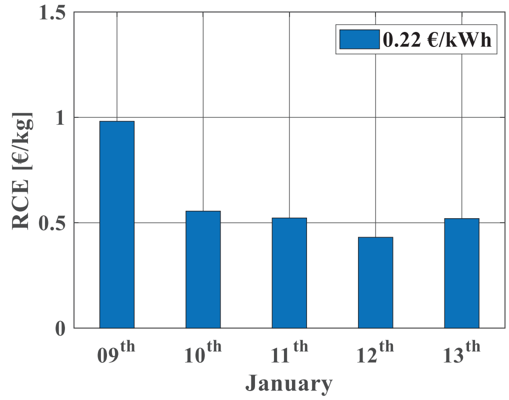
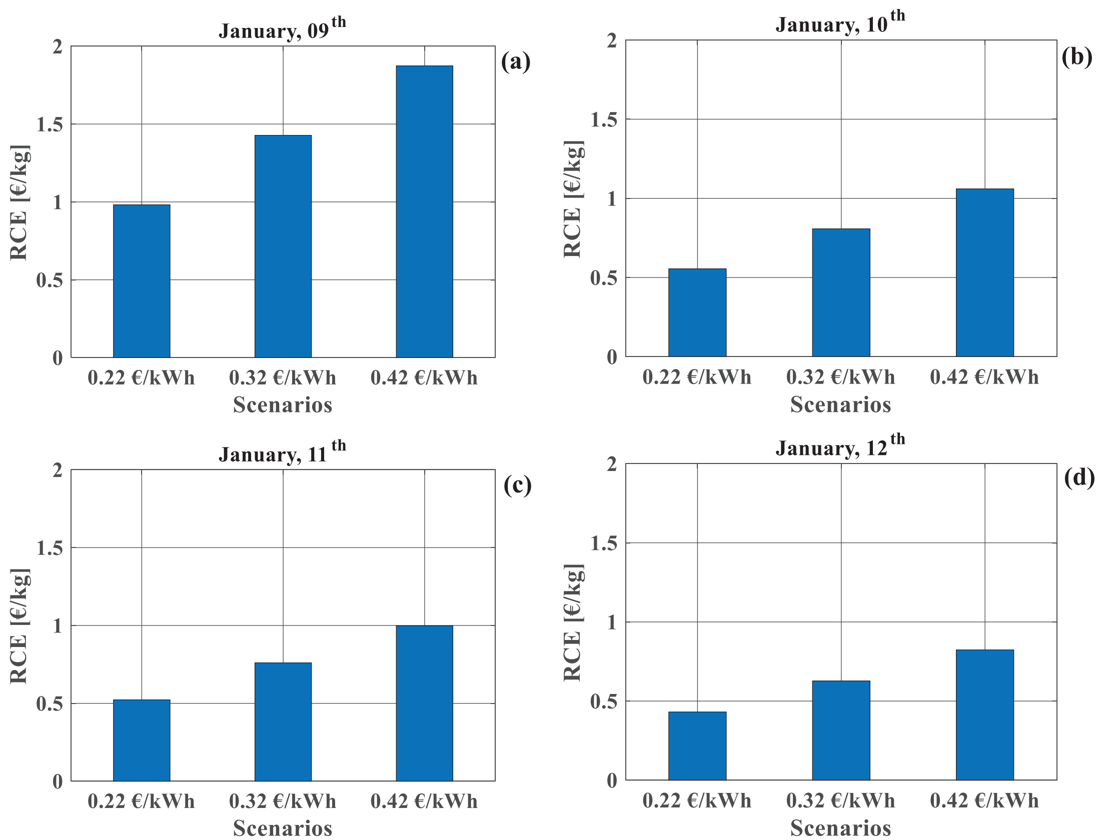


Figure 5 *- Daily rate of cost for electricity related to the kilogram of processed product for a specific cost of electricity of* $0.22\ €/kWh$ *for the second week of January.*

It can be noted that the daily RCE of January, 9th is significantly higher compared to the other ones, following the trend of the daily energy consumption shown in the previous sub-section (4.1): $+88\%$ and $+128\%$ compared to the ones of January 11th and 12th, respectively.

Finally, different economic scenarios have been considered by fixing the specific cost of electricity to $0.32\ €/kWh$ and $0.42\ €/kWh$, in order to take into account the variation of the specific cost of electricity. Results of the implemented scenarios are shown in Figure 6.



https://doi.org/10.52202/069564-0236

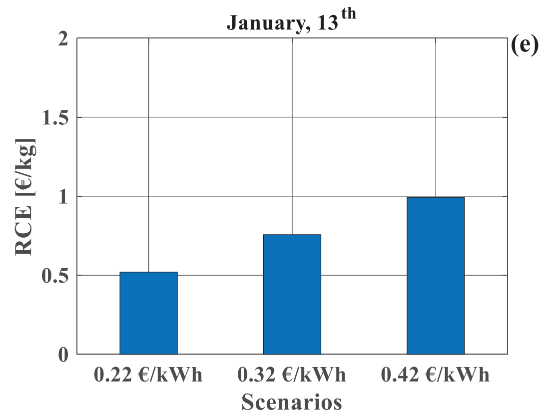


Figure 6 *– Daily rate of cost for electricity related to the kilogram of processed product for specific cost of electricity of* $0.22\ €/kWh$, $0.32\ €/kWh$ *and* $0.42\ €/kWh$. *(a) January, 9th. (b) January, 10th. (c) January, 11th. (d) January, 12th. (e) January, 13th.*

It can be noted that the increase in the specific cost of electricity involves an increase in the daily rate of cost for electricity per kilogram of processed product – $+92\%$ and $+94\%$ by passing from a specific cost of electricity of $0.22€/kWh$ to $0.42\ €/kWh$ by considering January 11th and 13th, respectively. The same trend is observed for all the operating conditions included in the analysis.

5. Conclusions

In this manuscript the modelling of a traditional agrifood system has been implemented taking into account all the parameters of interest, such as external conditions, internal ones, crop type production, air conditioning and lighting systems. In detail, data from a local farm producing salad have been processed in terms of quantity of product treated during the specific j-th processing phase m_p^j and its residence time inside the generic j-th cell $\Delta\vartheta_j$ as well as data about the refrigeration unit serving the whole plant and production lines with their on/off times. A thermo-economic analysis has been implemented by considering different operating conditions in terms of daily external temperature profile and specific cost of electricity. The main conclusions of the manuscript are reported as follow:

- For all the operating conditions considered and for all the days taken into account the thermal loads evaluation has highlighted that the thermal power exchanged with the external ambient through the walls and the roof of the plant is, at most, about the 20% of the outgoing thermal load of the evaporator during the lighting hours whereas the thermal load of the auxiliaries (including the production lines) is about the 80% of it.
- The total daily energy consumption related to the kilogram of processed product has been evaluated: for January 9th it is significantly higher compared to the others: $+77\%$ and $+128\%$ compared to the ones of January 10th and 12th, respectively.
- By considering the specific cost of electricity of January 2023 as $0.22\ €/kWh$, the daily rate of cost for electricity RCE has been evaluated. The same trend of the total daily energy consumption was found: in fact, the daily RCE of January 9th is significantly higher compared to the others, up to $+128\%$ with the one of January 12th.
- Finally, different economic scenarios in terms of specific cost of electricity have been included in the analysis. It was found that the increase in the specific cost of electricity involves an increase in the daily RCE, up to $+94\%$ for January 13th, by passing from specific cost of electricity of $0.32€/kWh$ to $0.42\ €/kWh$.

Nomenclature

a	absorption coefficient
A	surface area, m^2
G	solar radiation, W/m^2

h	heat transfer coefficient, W/(m^2 K)
H	height of the wall of the cell, m
k	thermal conductivity, W/(m K)
L	length of the wall of the cell, m
$\dot{L}$	mechanical power, kW
m	mass of processed product, kg
M	total processing phases
N	number of step integration
RCE	rate of cost for electricity, €/kg
T	temperature, K
$\dot{Q}$	thermal load, kW

Greek symbols

ϑ	angle of incidence of the solar radiation, rad
$\Delta\vartheta$	residence time of the mass during the processing phase

Subscripts and superscripts

amb	ambient
aux	auxiliaries
c	conductive
cell	cell
comp	compressor
ev	evaporator
ext	external
i	time step for the integration
int	internal
k	convective
j	specific processing phase
max	maximum
p	process
rad	radiant
raw mat.	raw material
step	step of integration
tot	total
wall	wall

References

[1] Fao. 2011. The state of the world's land and water resources for food and agriculture (SOLAW) – Managing systems at risk. Food and Agriculture, Organization of the United Nations, Rome and Earthscan, London.

[2] https://unesdoc.unesco.org/ark:/48223/pf0000225741_eng

[3] https://ec.europa.eu/eurostat/databrowser/view/NRG_BAL_S__custom_624870/default/table?lang=en

[4] Van Ruijven B J, De Cian E, Sue Wing I 2019 Nature Communication 10 2762

[5] United Nations, Department of Economic and Social Affairs, Population Division 2017 World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP/248.

[6] https://ec.europa.eu/eurostat/databrowser/view/AEI_FM_USEFERT/bookmark/table?lang=en&bookmarkId=4d3d0db8-76c1-4884-86e3-bdb23b1dae21.

[7] https://ec.europa.eu/eurostat/databrowser/view/AEI_FM_SALPEST09/bookmark/table?lang=en&bookmarkId=53792fd3-191d-4201-aab5-c01c67fd927c

 https://doi.org/10.52202/069564-0236

[8] Graamans L, Baeza E, van den Dobbelsteen A, Tsafaras I, Plant factories versus greenhouses: Comparison of resource use efficiency, Agricultural Systems 160 31-43, 2018

[9] Ohyama K, Yamaguchi J, Enjoji A, Resource Utilization Efficiencies in a Closed System with Artificial Lighting during Continuous Lettuce Production, Agronomy 10 723, 2020

[10] Kozai T, Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory, Proc Jpn Acad Ser. B, 2013

[11] Harbrick K, Albright L D, Comparison of energy consumption: greenhouses and plant factories, Proc VIII Int. Symp. On Light Horticolture, 201

[12] Stanghellini C 1987 Institute of Agricultural Engineering

[13] Righini I, Vanthoor B, Verheul M J, Naseer M, Maessen H, Persson T, Stanghellini C, A greenhouse climate-yield model focussing on additional light, heat harvesting and its validation, Biosystems Engineering 194 (2020), 1-15

[14] Weidner T, Yang A, Hamm M W, Energy optimization of plant factories and greenhouses for different climate conditions, Energy Conversion and Management 243 (2021), 114336

[15] https://www.arera.it/it/dati/condec.htm

https://doi.org/10.52202/069564-0236