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COOLING CHAMBERS POWERED BY RENEWABLE ENERGY SOURCES-PRESPECTIVES AND DESIGN ASPECTS FOR THE REGION OF NORTH GREECE

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ABSTRACT

The cooling process is of great importance in the agricultural and commercial sector. The conservation of agricultural products is considered as a necessary process in the food industry in order to ensure the sustainability of the food chain. However, the energy consumption and environmental effect of the cooling chambers use is a main issue. Renewable energy sources (RES) as the energy source of cooling chambers aimed to conserve agricultural products could be a solution to mitigate the negative effects of conventional cooling chambers use. In this work the perspective of using solar energy as a main source of energy for agricultural products' cooling chambers in North Greece is examined. The study includes the investigation of the current situation regarding the solar energy potential of the region, the agricultural products amounts and the proper design of the cooling chamber in order to succeed the optimum results.

Keywords: Cooling Chambers, Solar Energy, Agricultural Products, Energy Conservation, CO_2 Emissions.

I. INTRODUCTION

The conservation of agricultural products is of great importance for agriculture and the food industry in general. According to the U.S Department of Agriculture the cold storage of many agricultural products is a main part of the agri-food supply chain, including nuts, fruits, vegetables, meat, dairy and poultry products which can be either frozen or conserved in cold storage [1]. Proper conservation and storage of fresh fruits and vegetables is necessary for various reasons. For fresh fruits and vegetables which have high water content, the level of nutrients begins to decline after they are harvested. Proper storage conditions can delay the deterioration of fresh products. The storage conditions are not the same for each product- but in general a low temperature and medium to high relative humidity environment is considered as the best solution to avoid, at first, the dehydration of products [2], [3]. The variations of lowest safe temperatures of fruits and vegetables define, in a high percentage, the capacity of the cooling chamber. For potatoes and watermelons, the lowest safe temperature is about 3°C, while for okra, sweet peppers and eggplants is 7°C. On the other hand, cucumbers, ripe tomatoes and pumpkins can be conserved in 10°C [4]. Another problem which is confronted with low temperatures is that microorganisms (bacteria of fugi) aren't allowed to grow [5]. For farmers and primary production the cold storage of fruits and vegetables is a main issue as it helps conserve large amounts of products which are usually produced at the same period and these way they can be transported to the end users with a delay. The refrigeration or cold storage of agricultural products is mainly performed in cooling chambers which operate under the mechanical/vapor compression which is considered as one of the most reliable and fully developed methods [6]. This type of refrigeration is accompanied with energy consumption and when the cooling chamber is connected to the grid with CO_2 emissions generation. The energy cost of cooling chambers is a very important issue and it can affect the economical viability of agricultural activities. A general approach of energy consumption in cooling chambers for agricultural purposes is not an easy task as the energy consumption depends on the type of agricultural product, the region in where the chamber is installed and the machine capacity. However, in the literature, the energy consumption is a major issue. For large facilities the energy consumed in cold storage warehouses can be between 30-50kWh/m^3/year depending on many factors such as the quality of the structure and the temperatures that must prevail inside the storage facility, representing the 10-15% of the total operational costs [7]. In another research work conducted in Thailand, it was found that the specific energy consumption for chilled cold stores varied between 37 and 481 kWh/m^3 year, with this number to be increased when it comes to frozen cold stores [8]. The main energy consumption is performed at the compressor representing almost the 92% of the total energy consumption [9]. The cost of operation depends on electricity prices. Even though these machines operate with a good coefficient of performance due to the thermodynamic cycle they base their operation, the energy loads still remain relatively high due to the large amounts of products and as a result large volume stores. The initial cost of such installations (mechanical/ vapor compression) remains in low levels [10]. As far as it concerns the environmental effect of refrigeration of agricultural products, it is classified as on of the main Greenhouse gas emissions (GHG) in agriculture [11]. In particular it is considered as one of the main contributors of GHG of the downstream supply chain [11]. According to the literature the percentage of GHG caused by refrigeration of agricultural products is about 1% of the total GHG emissions [12].

Taking into account the up mentioned, it occurs that the cold storage and conservation of fresh fruits and vegetables is a crucial issue for farmers for several reasons. On the other hand the operation of conventional cooling chambers is accompanied with energy consumption and as a consequence CO_2 emissions production. A solution to this problem is to adopt alternative cooling techniques or to use renewable energy sources for electricity generation. An alternative method that is mentioned in the literature is evaporative cooling [13], [14]. This method is based on the evaporation process which usually has lower cooling capacity than the typical cooling chambers follow the compression vapor thermodynamic cycle. Also a lot of research has been conducted concerning the uses of renewable energy sources or passive elements for cooling chambers. In most of the works the insulation of the cooling chamber is improved, or the introduction of Photovoltaic technology or absorption chillers driven by solar energy are introduced [15], [16], [17].

In this work it will be investigated the potential of North Greece in terms of agricultural production and climatic conditions in order to evaluate whether the installation of cooling chambers for agricultural products can be a feasible option for the farmers. This work is of great interest for farmers and experts on the field of agricultural products equipment and the logistics, as it provides a method that can be adopted in any region along with a preliminary- proposed design of cooling chamber adjusted to the needs of the products and region.

II. METHODOLOGY

In order to evaluate the potential of the region for the installation of PV powered cooling chambers the following data should be analyzed:

1. Solar energy potential of the region in order to evaluate the capability of the region to support PV systems for cooling chambers
2. The type and amount of production and the required conservation conditions
3. The preliminary design of the chamber including the required capacity due to the energy removal of fruits, constructive characteristics, equipment and identical initial costs

Region and solar energy potential

For the scope of the study one of the most productive regions of North Greece will be evaluated as shown in the map of Figure 1 [18]. The region is well- known for the production of peaches and apricots. The data regarding the solar potential will be received by the solar atlas platform [19]. Taking into account the statistics of the region due to Solar Atlas Platform the general statistics of Table 1 occurs. According to these statistics a first approach regarding the potential of the area in terms of electricity generation can be obtained. However, in Table 2 the average monthly solar radiation data are presented. These data are also useful for the scope of the study since the solar energy is not available with the same intensity all year long, as well as, the cooling needs for products preservation. Usually during the summer the production is on its peak so the electricity needs are higher. The data in Table 2 occur from 5 specific crucial points of the selected region due to the productivity rates. Since there is a possibility of autonomous or connected to the grid systems, the option of net metering operation where the surplus of energy production during periods that it is not consumed can be used in periods where the energy amounts are not enough. This approach is very important for agricultural products cooling since the production is only available for specific periods, so the energy produced in other periods (even not so intense) can be used to cover increased needs during the summer. In order to estimate the energy generated in the current region Equation (1) can be used as it is taken by the literature [20]:

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$$Egen=It \times Am \times \eta_1 \times \eta_2 \quad (1)$$

Egen: Electricty generation by the PV system (Wh/hour)

Am: Average module surface (m^2)

η_1: PV electrical efficiency of module (depended on the angle of installation, type of module, temperature etc)

η_2: inverter efficiency (The efficiency of the inverter when transposing the DC electricity output to AC electricity output)

It should be noticed that the above equation will be used to make a preliminary estimation for the region estimation.

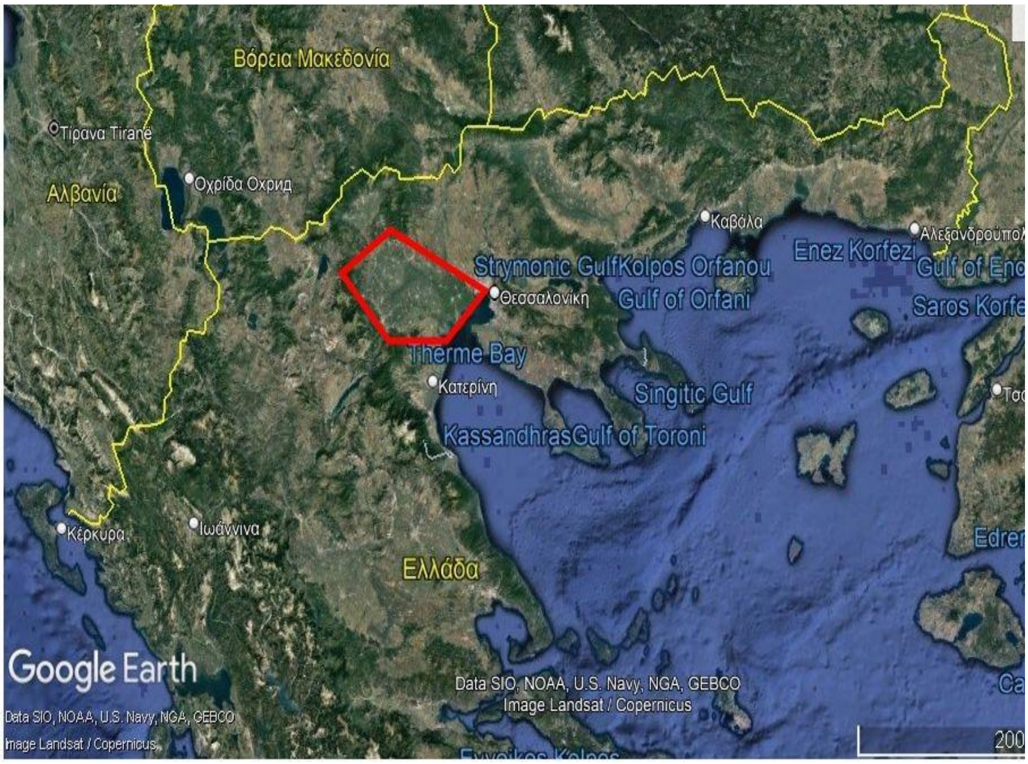

Figure 1. Study area definition [18]

Table 1. Minimum and maximum values of parameters regarding the solar energy potential and electricity generation [19]

Parameter	Min value	Max value	Units
Specific photovoltaic power output	3,97	4,11	kWh/kWp
Direct normal irradiation	4,21	4,37	kWh/m^2
Global horizontal irradiation	4,27	4,39	kWh/m^2
Diffuse horizontal irradiation	1,73	1,75	kWh/m^2
Global tilted irradiation at optimum angle	4,92	5,07	kWh/m^2

Table 2. Average hourly profiles of direct solar irradiation of the selected region (Wh/m^2)

hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1	0	0	0	0	0	0	0	0	0	0	0	0
1 - 2	0	0	0	0	0	0	0	0	0	0	0	0
2 - 3	0	0	0	0	0	0	0	0	0	0	0	0
3 - 4	0	0	0	0	0	0	0	0	0	0	0	0
4 - 5	0	0	0	0	10	22,6	12,8	0,2	0	0	0	0

5 - 6	0	0	0,8	33,2	108,6	154,8	136	61,8	17,2	0	0	0
6 - 7	0	8,6	67,2	152,4	244,6	313	306,4	216	151,2	69,2	12,2	0
7 - 8	63,2	132,2	212,8	274	353,2	435,6	440,2	375	307,2	216,8	120,4	65,6
8 - 9	220,8	287	338,8	359,6	435,6	532,6	549,4	488	412,8	334,6	246,6	203,6
9 - 10	334,6	367,6	412,2	420,6	491,6	596,6	632,6	572,4	487,6	401,2	313,8	301,6
10 - 11	384,8	413	455,6	447,6	517	626	677,6	619,2	521,6	436,6	351	339,8
11 - 12	406,4	438,4	468,6	454	514,2	625	687,2	639,8	525,8	448	367	355,2
12 - 13	416,6	444,2	464,4	443,4	498,2	607,8	677,8	634,6	516,2	444,6	371	357
13 - 14	398,6	431,8	448,8	421,4	474	572,2	648,2	607	485,8	421,2	350,6	340,2
14 - 15	355,4	391,2	406,8	380,6	428,6	521,2	592,6	550,2	438,2	366,4	297,4	292,8
15 - 16	234,2	322,6	350,4	327,8	370,2	453	519	471	370,6	271	162,8	153,6
16 - 17	66	151,8	253	262,6	301	376,6	431	372,8	244	101,8	36,2	33,6
17 - 18	0,2	24	89,4	131,8	196,2	279	318,4	205	76,2	8,2	0	0
18 - 19	0	0	6,4	27,6	59,8	122,6	130,2	48	2,8	0	0	0
19 - 20	0	0	0	0	0,8	18,2	15,4	0	0	0	0	0
20 - 21	0	0	0	0	0	0	0	0	0	0	0	0
21 - 22	0	0	0	0	0	0	0	0	0	0	0	0
22 - 23	0	0	0	0	0	0	0	0	0	0	0	0
23 - 24	0	0	0	0	0	0	0	0	0	0	0	0

Type and amount of products- conservation conditions

In the selected regions the main production is fruits and especially stone fruits with peaches and cherries to cover the greatest percentage according to the data of the Hellenic Statistical Authority [21]. The evolution of total amount of area cultivated for these fruits and percentage of the total production area of stone fruits is highlighted in Figures 2 and 3 for the years 2017-2019. Taking into account data from producers the average production in 0,1ha is almost 3 tons per year. Peaches in general have a short storage life (almost 2 weeks). The optimum storage conditions for peaches are 0^oC [22]. The range which is considered acceptable is $-1,5^oC$ to 1^oC, but in general peaches should not remain in such storage conditions for more than 2 weeks, as the negative effects of chilling injury occurs [22].

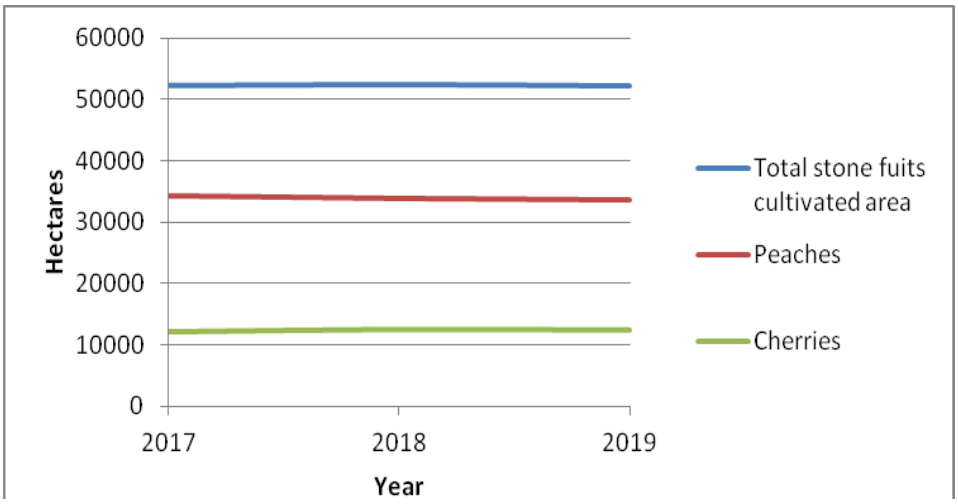

Figure 2. Annual evolution of the cultivated area of stone fruits and the 2 primary categories for the years 2017-2019 for the region of Central Macedonia

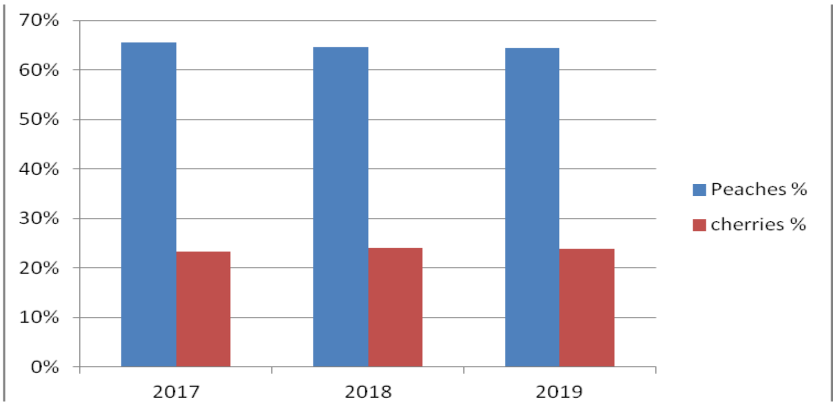

Figure 3. Annual evolution of the percentage of the cultivated area of stone fruits and the 2 primary categories for the years 2017-2019 for the region of Central Macedonia

Energy analysis and preliminary design of cooling chambers

For the calculation of the power capacity of the cooling chamber the energy exchanges amounts should be considered. The energy exchange taking into account in cooling chambers are the heat losses from the walls and infiltration and the heat gains by the products stored in the chamber. In general more heat exchanges can be taken into account such as heat losses from door openings or heat gains by workers or lights which are not constant. However, in this preliminary design approach these energy exchange amounts will be added in the result of the main energy exchanges as an increment percentage of 10%. The heat losses calculation rationale below includes heat losses from the walls (which are actually heat gains since the external temperature is higher than the storage temperature in warm periods) and heat gains from the fruits as described in the literature [23]. Heat losses from infiltration will be considered negligible since the chamber is new and well manufactured. The heat losses from the walls are described in equation (2)

$$Qw=U\times A\times DT \qquad (2)$$

Qw: Heat exchnage from walls (kW)

U: Overall heat transfer coefficient (W/m^2K)

DT: Temperature difference between the cooling chamber internal environment and ambient environment temperature (^oC)

$$Qp=m\times cp\times DT \qquad (3)$$

Qp: Products cooling loads (kJ)

m: products mass (kg)

cp: Product specific energy (kW/kg K)

DT: temperature difference between inlet temperature and storage temperature (^oC)

$$Qr=m\times resp \qquad (4)$$

Qp: Products loads due to respiration (kJ)

m:products mass (kg)

resp: Respiration rate of the product (kW/kg)

The total cooling load is calculated by equation (5)

$$Qtot=Qw+Qp+Qr \qquad (5)$$

III. RESULTS

PV output potential calculation

Considering equation (1) and the data from Table 2, the potential energy production for each month occurs as shown in Table 3. For the calculation a typical value for η_1 was chosen (about 10%) [24], while for η_2 according to the literature the value is about 95% [25].

Amount of production

According to the data presented in Figures 2 and 3 and the fact that for each 0,1ha of cultivated field 3tons of peaches are produced, the total amount produced peaches is calculated as an average of the 3 years to 1018271 tons. These amounts are not equally divided through the year. The fruits are collected during June- July and August. Also it should be noticed that these amounts concerns the whole region of Central Macedonia and not only the selected region. This region though is the main producer of Greece in total (about 60-70%). So the amounts that will be considered that are required to be conserved will be about the 30% since some of them are directly distributed to the local markets or the industry. So this amount equals to 305481 tons.

Table 3. Average hourly profiles and daily total PV output electricity for the selected region (Wh/m^2)

hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
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
1 - 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
2 - 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
3 - 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
4 - 5	0,0	0,0	0,0	0,0	1,0	2,1	1,2	0,0	0,0	0,0	0,0	0,0
5 - 6	0,0	0,0	0,1	3,2	10,3	14,7	12,9	5,9	1,6	0,0	0,0	0,0
6 - 7	0,0	0,8	6,4	14,5	23,2	29,7	29,1	20,5	14,4	6,6	1,2	0,0
7 - 8	6,0	12,6	20,2	26,0	33,6	41,4	41,8	35,6	29,2	20,6	11,4	6,2
8 - 9	21,0	27,3	32,2	34,2	41,4	50,6	52,2	46,4	39,2	31,8	23,4	19,3
9 - 10	31,8	34,9	39,2	40,0	46,7	56,7	60,1	54,4	46,3	38,1	29,8	28,7
10 - 11	36,6	39,2	43,3	42,5	49,1	59,5	64,4	58,8	49,6	41,5	33,3	32,3
11 - 12	38,6	41,6	44,5	43,1	48,8	59,4	65,3	60,8	50,0	42,6	34,9	33,7
12 - 13	39,6	42,2	44,1	42,1	47,3	57,7	64,4	60,3	49,0	42,2	35,2	33,9
13 - 14	37,9	41,0	42,6	40,0	45,0	54,4	61,6	57,7	46,2	40,0	33,3	32,3
14 - 15	33,8	37,2	38,6	36,2	40,7	49,5	56,3	52,3	41,6	34,8	28,3	27,8
15 - 16	22,2	30,6	33,3	31,1	35,2	43,0	49,3	44,7	35,2	25,7	15,5	14,6
16 - 17	6,3	14,4	24,0	24,9	28,6	35,8	40,9	35,4	23,2	9,7	3,4	3,2
17 - 18	0,0	2,3	8,5	12,5	18,6	26,5	30,2	19,5	7,2	0,8	0,0	0,0
18 - 19	0,0	0,0	0,6	2,6	5,7	11,6	12,4	4,6	0,3	0,0	0,0	0,0
19 - 20	0,0	0,0	0,0	0,0	0,1	1,7	1,5	0,0	0,0	0,0	0,0	0,0
20 - 21	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
21 - 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
22 - 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
23 - 24	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Total energy	273,7	324,2	377,6	393,0	475,3	594,4	643,6	556,8	432,9	334,4	249,8	232,1

Energy analysis calculation

For Equation (1) the U value which is concerns a 10mm Polyurethane panel, so the U-value is taken 0,249 (W/m^2 K) as it is referred in the literature [26]. The surface of the chamber will be referred to an amount of 1m^3 volume which can be consisted by a cubical chamber with dimensions 1m x 1m x 1m. This is a reference value which can be adjusted to any given volume. So for such a cubic chamber there are 6 sides of 1m^2 surface.

That means that the total surface is $6m^2$. However the $1m^2$ which is installed in the ground is considered to have negligible losses or gains. The temperature difference is equal to 30ºC as it is considered that the PV panel will provide shade to the chamber in the case the system is autonomous and it is installed in a field. In any case the chamber should be shaded to avoid large external temperatures. So, the external temperature for the region under shade during the summer is 30ºC [27], while the internal temperature should remain in 0ºC. So the maximum load occurs Qw=37,45W, in an hourly range the heat gain is 37,45Wh . For the products heat gains, the volume and relevant mass that can be stored in such a chamber must be defined. Taking into account the packaging methods of peaches in boxes [28] with specific dimension the amount of peaches that can be stored in $1m^3$ is about 280kg. If it is assumed that the inlet temperature is about 15ºC during warm periods because it is chosen to pre stored in a warehouse. The cp for peaches is 3,892 kJ/kg K [29]. So this amount of energy is calculated 21784kJ or 6075Wh. If it is assumed that the peaches remain there for 48hours in an hourly basis the amount of energy required is Qp=94,92Wh. For the heat gains due to respiration, the respiration rate of peaches is necessary. According to the literature peaches heat release due to respiration varies between 11-19 mW/kg [30]. An amount of 15 mW/kg will be chosen as an average value. So the total amount according to equation (4) will be 4,2Wh which divided to 48 hours again will be Qresp=0,0875Wh per hour. The total required energy to be removed is about 132,45Wh per hour.

IV. DISCUSSION

As it occurs from the results there is a significant potential to cover a big part of peaches cooling in the examined region. For the months of June, July and August the average daily production of a $1m^2$ PV panel is 594 Wh, 643,6Wh and 556,8Wh respectively. The cooling chamber is assumed to operate about 10 hours per day or even less. So the energy amount needs to be removed is about 1324,5Wh. That means that without any additional energy the 44% of the load can be covered during June, the 48,5% during July and the 42% during August. In order to cover the full capacity a $2,37m^2$ will be necessary. If the system is operating with the method of net metering, than all the energy produced during the rest of the months can be used to cover the energy needs of the chamber. In fact, the period between March and May and September to October is enough to cover these needs. In the case all the energy of the year was utilized the chamber could be 32% larger. The above observation has to do only with the $1m^3$ basic unit. According to the data concerning the production of the whole region the cooling chambers estimated volume for the whole region should be about $1091000m^3$. This volume capacity must be divided in various sizes depending on the rationale of installation. For example, in the case of large warehouse-type cooling chambers the capacity can be $1000m^3$. For such an installation the PV installation should be at least $100m^2$ and cover part of the needs (about 15-20%). If the volume concerns individual farmers with volumes between $20\text{-}30m^3$, the installation of a $20m^2$ PV systems could cover the whole need. Other issues that should be taken into account are the transportation- logistics issues which can affect the viability of central facilities. In any case it seems that there is both a significant potential of solar energy in the region that can be utilized as an energy source for the chambers as well as a great potential of primary production that it is required to be properly and sustainable stored.

V. CONCLUSION

In this work, the potential of performing cooling in a productive area of Greece with the use of solar energy was investigated. The region has a very large production of peaches and faces many challenges regarding the management of production. In the study it was found that the solar energy potential could cover a great percentage or full needs of the examined case study. This study is a preliminary study which scope is to examine if there is potential needs both in terms of production and available energy to follow such a practice in actual projects. In order to fully develop the examined practice economical and environmental gains should also be examined. However, the results are of great importance for the further steps towards the modernization of the practices that are used in the agricultural sector in Greece.

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