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Review on solar cooker systems: Economic and environmental study for different Lebanese scenarios

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ABSTRACT

In this work, a review on solar cookers is presented. This review includes principle and classification, parameters influencing the performance of a solar cooker, and energy and exergy analysis related to solar cooker systems. Moreover, an economic study is performed for different scenarios in Lebanon (home, hotel, restaurant and snack) and for several categories of solar cookers (solar box cooker, solar panel cooker, parabolic solar cooker and evacuated tube solar cooker with thermal storage). The main idea of the economic study is to estimate the payback period in function of percentage of time Pr where solar cooker is utilized, for each solar cooker and in each scenario. It was obtained that the higher dependence on solar cooker decreases payback period. Besides, environmental analysis is implemented to compute the amount of reduction in carbon dioxide emissions in the different scenarios as percentage of time where solar cooker is used varies. It was shown that the reduction in amount of carbon dioxide raised from 6.05 to 60.55 kg/month, 605.52 to 6055.2 kg/month, 399.64 to 3996.43 kg/month and from 90.82 to 908.28 kg/month in home, restaurant, hotel and snack respectively when Pr increased from 0.1 to 1. Hence, utilizing a solar cooker diminishes carbon dioxide emissions in all scenarios where P_r has direct relationship with minimization of carbon dioxide emissions.

1. Introduction

During the last centuries, world energy demand relied to a great extent on fossil fuels. Annually, energy consumption progresses by an average of 1% in developed countries and 5% in developing countries [1,2]. Due to the continuous rise in energy demand, several expectations reveal that fossil fuel will not meet this growing demand and its cost will definitely increase sharply. Thus, the mounting cost of fossil fuel in addition to some environmental issues such as pollution, greenhouse effect, global warming, etc., gave renewable energy [3–8] a remarkable interest at the international level during the last years. Renewable sources of energy are environmentally friendly and they are supplying about 14% of the world energy demand which will ascend in the future [9]. Indeed, solar energy occupies the throne of renewable energies. It is estimated that solar energy falls on the surface of the earth at an average of 120 pet watt. This reveals that solar energy received to the earth in one day is equivalent to energy demand required in 20 years. International Energy Agency showed that in year 2050 solar energy can supply approximately 45% of the world energy request [10].

Solar energy is used in a large diverse of applications that can be divided into two types of systems [11]: systems that rely on converting solar energy into thermal energy to be used for different purposes [12], and systems that transform solar energy directly into electricity by photovoltaic technology [13]. Solar energy can be categorized also according to the type of solar collector [14,15]. The main role of solar collector is to gather solar radiation, transform it into heat and transport it to a working fluid. Fig. 1 illustrates the major categories of solar energy and their types.

Solar cooker [1,16–19] is harnessed for cooking food, pasteurizing and sterilizing. Solar dryers [20–25] are used in agricultural and industrial products for mitigating bacterial growth and preserving them by removing moisture. Solar water heating systems [26–31] heat water for domestic and industrial purposes. The heated water in the storage tank flow through a coil to heat air directed to the coil by a fan and enters to the space and heat it [32–36]. Solar space cooling and refrigeration [37–42] are utilized for refrigerating medicines or food, or cooling space. Concentrated solar power [43–48] uses mirrors and lenses to concentrate solar energy and thus generating heat and power indirectly. Photovoltaic systems [49–54] convert sunlight directly into electricity by the absorption of photons.

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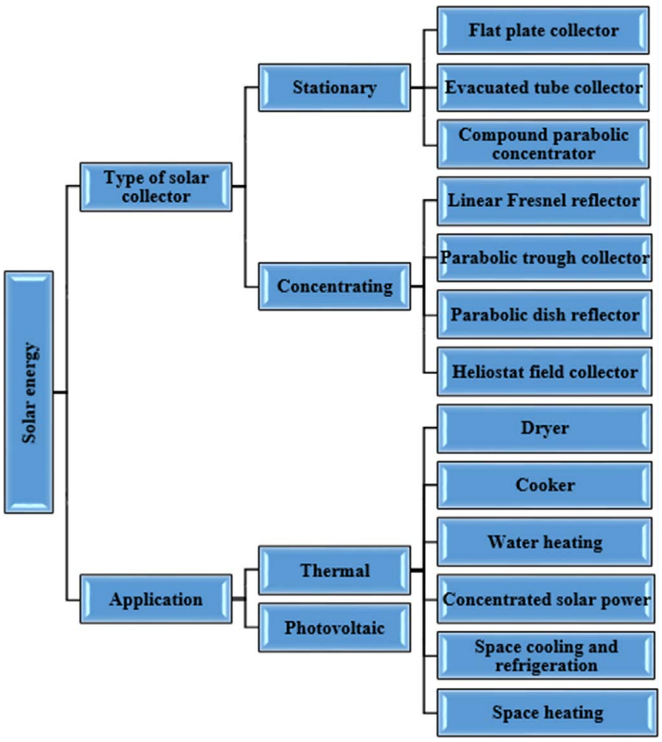

Fig. 1. Classification of solar energy.

Solar cooker is one of the most significant solar energy applications. Energy required for cooking represents about 36% of the global primary energy consumed [55]. Hence, solar cooker has a great potential in the domestic sector.

Fig. 2 shows the number of studies conducted on solar cookers from 1990 to 2016. It is shown that the number of researches on solar cookers is striking of all over the years and especially for the last four years. This explicates the magnitude of solar cookers as a solar energy device and its capability of being vital application in the coming years. In this context, the present work concerns a review on solar cooker technology. It presents particularly the principle, classification, and parameters affecting the performance of a solar cooker. Also, Energy and exergy analyses are exhibited. Moreover, environmental and economic concerns are presented to highlight the requisite role of solar cooker on both fields and for several scenarios in Lebanon country.

Section 2 of the paper presents the principle and classification of solar cooker. Section 3 delineates the effective parameters that impact the solar cooker performance. Section 4 is devoted to energy and exergy analysis. In Section 5, economic and environmental concerns are exposed. Section 6 draws the main conclusions of the work.

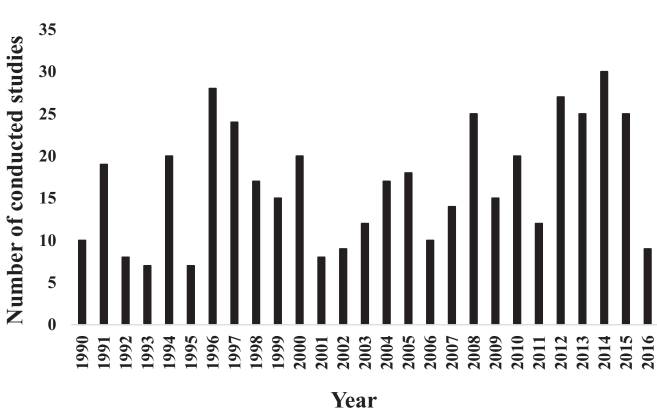

Fig. 2. Number of solar cooker studies over the years.

1.1. Historical note

Cooking food was unknown before the age of civilization, people used to eat food in its condition as they found it [56]. In 1767, Horace de Saussure, a French-Swiss physicist built box to cook fruit using solar energy where it reached temperature to 88 °C. In 1830, an English astronomer named Sir John Herschel tried to cook food in an insulated box cooker during campaign to South Africa. W. Adams progressed oven of octagonal shape made up of 8 mirrors in 1876. He stated that the oven cooked in two hours lots for seven soldiers. In 1945, Sri M. K. Ghosh, an Indian pioneer fabricated the first trade box type solar cooker. Dr. Metcalf and his student Marshall Longvin carried out water pasteurization using solar box cooker in 1979 [16]. In these days, solar cooker became a favorable application in which it provokes utilization of environmentally friendly renewable sources of energy and reduces dependence on conventional power sources. Due to its importance, various numerical, analytical and experimental studies [57–65] have been performed to enhance power capacity of solar cookers, evaluate its performance and identify parameters which help in optimizing it.

2. Principle and classification of solar cookers

Solar cooker is a viable and with great facility application of solar energy. Otte [66] briefly defined solar cooker as it is a way to exploit energy of sun in order to cook. Several studies [19,67–69] described the principle of solar cooker. Hence, solar cooker is an appliance that absorbs solar radiation, transfers it into heat, retains the heat and transmits it to food through cooking pot walls. It can be used for heating or cooking food or drink. Also, it can be utilized to achieve vital processes mainly pasteurization and sterilization.

Many sorts of solar cookers may be found in the literature. Moreover, new solar cookers designed with new improvements are continuously proposed, which requires continuous update of solar cooker classifications. However, it can be confirmed that solar cookers can be categorized into direct and indirect type according to the heat transfer mechanism to the cooking pot [18]. Sedighi and Zakariapour [17] presented a review on direct and indirect solar cookers with experimental, numerical and theoretical analysis to evaluate performance and compare efficiency of solar cookers. Box, panel and concentrated solar cookers are under the direct type. Indirect type is categorized according to the solar collector used, or energy storage. Cooking process in the direct type occurs by using sunlight directly, whereas in the indirect type, heat is transferred to the cooking unit using a heat transfer fluid. Fig. 3 represents a diagram showing the main types of solar cooker. Regattieri et al. [70] implemented an easy-use portable solar cooker by reutilizing cardboard packaging waste. Such device is demonstrated to complete kitchen-set for humanitarian people to solve problem of fuel and wood leakage. The cooker can be utilized for heating, cooking meals, boiling water and purifying raw water from rivers and lakes. Several cooker prototypes were designed, developed and tested by the authors to determine the optimum shape and predict the efficiency of the solar cooker. The results showed that parabolic configuration yields that best results where its efficiency ranges between 14% and 18%.

2.1. Direct solar cooker

2.1.1. Solar box cooker

Box type solar cooker [71–75] consists of an insulated box with single or double transparent window made up of glass or plastic. Solar radiation passes through the transparent window and is absorbed by the cooking utensils, the walls and the bottom of the cooker [76]. The inner part of the box and the cooking pots must be painted in black color to maximize the heating effect [77]. The window provides a greenhouse effect in which it permits the passage of solar radiation but prevents it to get out from the cooking vessel [78]. Thus, heat

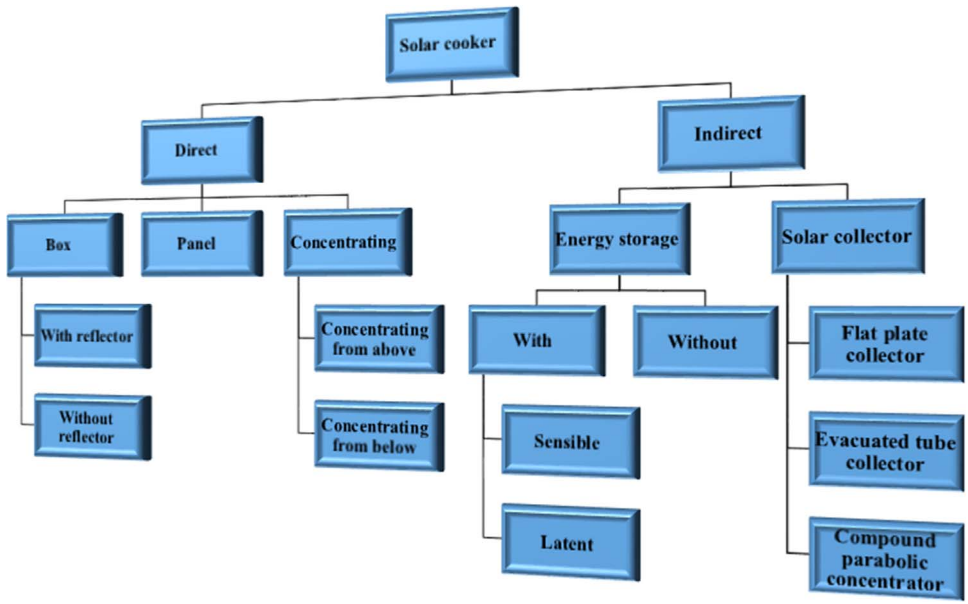

Fig. 3. Classification of solar cookers.

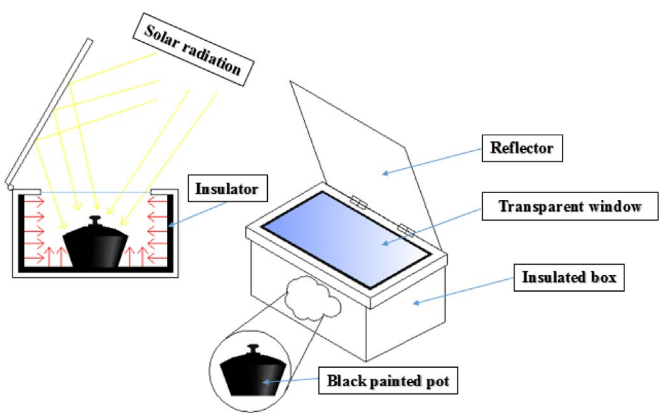

Fig. 4. Solar box cooker with reflector.

radiations coming from the cooker`s walls and the cooking pots will be trapped inside the box heating the air. The double window reduces conduction which symbolized that it is better than the single one. In addition to that, on the side top of the box a reflector can be placed to reflect sun light into the box where maximum four cooking pots can be placed inside it. Fig. 4 shows a schematic diagram of box type solar cooker and its components. Farooqui [79] investigated improved power solar box cooker with free tracking system. It was found from the experimental results that the system tracks the sun for up to six hours. Lahkar and Samdarshi [80] reviewed thermal performance parameters of solar box cooker and the test procedure for these parameters. In addition to that, these parameters were used to derive objective parameters from simple relations. It was concluded that the objective parameters are able to supply all needed information to determine most convenient solar cooker regarding climate and geographical location, with the help of performance parameters that are independent on external factors. Harmim et al. [81] designed a novel solar box cooker integrated with compound parabolic concentrator. Also, heat transfer process of this cooker was modeled mathematically. The cooker contains utensil laden with water and deposited on the floor of the box. The purpose of the model was to study the effect of diverse parameters such as solar radiation, load of water and clouds on the dynamic behavior of the cooker. Joshi and Jani [82] designed Small Scale Box type Hybrid solar cooker coupling both thermal energy and photovoltaic. This cooker weight 6.5 kg and it is a modified design of Small Scale Box type solar cooker of weight 4.8 kg. the cooker was integrated with 5 panels of 15 W each. The experimental results reveal that reduction in cooking time due to the increase of input power (thermal power added to it photovoltaic power). It was also found that the Improved Small Scale Box type Hybrid solar cooker has an average efficiency 38% greater than the efficiency of Small Scale Box type solar cooker (30%). In addition to that, the estimated cost of the Improved Small Scale Box type Hybrid solar cooker is $120 and it is predicted to decrease to make it more favorable and likeable. Such research offers an idea to optimize the performance of a solar cooker by adding solar panels to it and exploiting photovoltaic power. However, improving the solar cooker performance can be achieved by other methods and cheaper than photovoltaic panels like enhancing configurations of the solar cooker, type of insulations, absorber tray and the cooking pot, using additional reflector, etc.

Box-type solar cookers have manifold profits [83] which make it favorable for usage. First, it uses direct and diffused radiations. Second, they are easy to handle and operate, in which they don't need tracking. Also, they require little intervention from the user since the moderate temperatures make stirring unnecessary. In addition to that, several vessels can be placed in it, and they can be kept warm due to the retained heat [84]. Box types are relatively inexpensive and they can be produced or repaired easily. Nevertheless, there are some hindrances of box solar cooker which can be illustrated by slow cooking process due to low temperature, cooking must be limited to daylight and it can't be used for frying or grilling.

2.1.2. Solar panel cooker

Solar panel cookers [85] are similar to solar box cookers in their principle of operation. But the panel cooker utilizes large reflective panel instead of insulated box to focus sunlight on the black cooking vessel that converts sunlight into heat energy. Besides, it has easy construction and low cost material in which it can be built from a single cardboard box and some aluminum foil. The pot is surrounded by a transparent cover which prevents heat from escaping and trap it, providing greenhouse effect. Solar panel cooker and its components are illustrated in Fig. 5.

Panel cooker's performance are extremely affected by the reflected radiation, thus it doesn't seem to be effective under dark, windy or cloudy weathers. Also, it should be placed in direct sunlight for several hours before it became ready to be used. Panel cooker can bake breads and cakes but it can`t fry food. “CooKit” is the most widely used cooker,

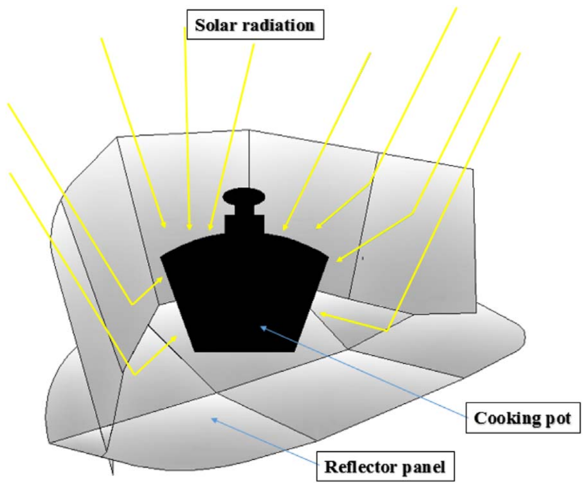

Fig. 5. Solar panel cooker.

it was developed and produced by a volunteer group of engineers and solar cooks associated with the Solar Cookers International, in 1994.

2.1.3. Solar concentrating cooker

Concentrating solar cooker [1,56] cooks food directly by absorbing the heat from the sun light without any interference of any material between the sun light and the cooking pot. It relies on the principle of solar optics in which it concentrates direct solar radiation on the bottom of the cooking pot to heat it and achieve extremely high temperatures. Concentrating cooker is formed of a parabolic reflector, cooking pot which is placed on the focus point of the cooker [76] and a stand as a support with turning mechanism to keep the reflector facing the sun. Fig. 6 shows a schematic drawing of the parabolic solar cooker. The two major kinds of concentrating cookers are: cookers concentrating light from above and cookers concentrating light from below.

Parabolic solar cooker is characterized by short cooking time due to the high temperature that it can be achieved. Also, some of the parabolic cookers can be utilized for baking [86]; however, this type of cookers requires the user`s attention due to the risk of fires and burns that it may cause.

2.2. Indirect solar cooker

Indirect solar cooker consists of a collector to gather heat and cooking part to exploit the yield. The cooking vessel is displaced from

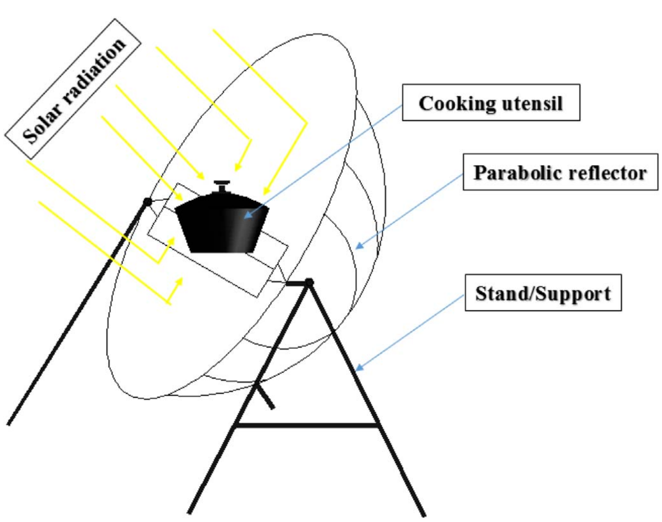

Fig. 6. Solar concentrating cooker.

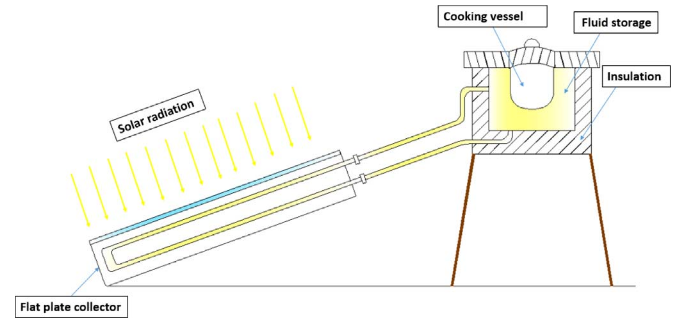

Fig. 7. Indirect solar cooker with flat plate collector.

the collector in which it is separated and protected from radiation. Heat is transferred from the collector to the cooking pot by a heat-transferring fluid, where a small circulating pump may be utilized to circulate the working fluid especially when the collector is kept at height above the cooking unit. On the other hand, a manual control valve orients the heat transfer fluid flow rate to the pot or to the storage tank.

Indirect solar cookers are commonly categorized according to the type of collector [87] used whether it is flat plate collector, evacuated tube collector [88,89] or compound parabolic concentrator. Fig. 7 shows a schematic diagram of an indirect solar cooker with flat plate collector.

In an indirect solar cooker, it is possible to cook in a separate place or to store energy during sunshine as a sensible or latent energy, and exploit it later (during evening, night or cloudy weather) [90–92]. In other words, indirect solar cookers may have sensible or latent heat storage; or it may not [93]. The thermal storage increases the performance and competitiveness of the solar cooker significantly, and optimizes the utilization of the energy collected since solar irradiation is irregular.

Sensible heat storage is the simplest form to store the thermal energy, in which it occurs by raising the temperature of a solid or liquid [94,95]. Fig. 8 illustrates an indirect solar cooker with sensible heat storage. The heat transfer fluid moves to the cooking unit after it had been heated in the collector, where part of its sensible energy is transferred to the double-walled cooking pot. Water, rocks, iron and oil are the main sensible heat storage media that have increasing heat capacity with temperature, which makes them motivating options for storing energy. Storing thermal energy allows cooking at night and reaching high temperature in short time, as well as keeping food warm for longer time. But the limitation of sensible systems is that most materials have small capability to store sensible heat.

Mawire et al. [96] compared experimentally the performance of thermal energy storage oils for solar cookers during charging. Experiments were carried on using an insulated 20 L storage tank, and three thermal oils: Sunflower Oil, Shell Thermia C and Shell Thermia B are used to be tested and evaluated. It was concluded from the experimental results that under high power charging, Sunflower Oil

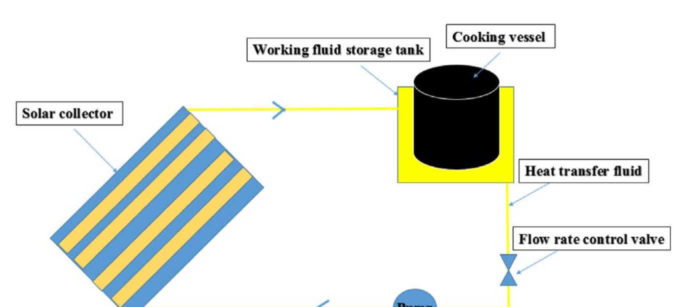

Fig. 8. Indirect solar cooker with sensible heat storage.

has the best performance between the other tested thermal oils.

Latent heat storage exploits the stored energy by using Phase Change Material (PCM) which allows to store significant amount of energy over narrow temperature range [97,98]. PCMs are characterized by their high thermal energy storage capacity, they have the ability to absorb energy during heating process and release it to the environment during cooling process. For example, during solid-liquid phase change, fusion absorbs energy and solidification releases it. Some of the latent heat storage materials that can be selected for solar cooking are: magnesium nitrate hexahydrate, magnesium chloride hexahydrate and stearic acid, acetamide, acetanilide and erythritol [99–103]. Energy storage has an essential role in retaining energy, upgrading reliability and performance of energy systems, as well as minimizing mismatch between supply and demand.

Nkhonjera et al. [104] presented a review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage. The authors stated in their paper that the most potential and vital issues of research in heat storage for cooking are the implementation of high temperature thermal storage units, progress in their geometry in addition to their heat transfer characteristics. Lecuona et al. [105] investigated experimentally portable parabolic type solar cooker combined with heat storage based on phase change material. A numerical modeling is performed to identify the climatic conditions of Madrid and to prove the experimental results. Technical grade paraffin and erythritol are the two checked phase change materials. It was obtained by the results that cooker with heat storage along the day can cook lunch for a family. Also, cooking the dinner and breakfast for the next day is possible if the pot is placed inside insulated box. Singh et al. [106] experimentally compared thermal performance of solar cookers with different heat transfer fluid (water and oil). Also, phase change material discharged was studied depending on the effect of gate valve. Commercial grade acetanilide was utilized as phase change material. The results revealed that the temperature of phase change material at 18:00 h was 10.7 °C when valves are closed, more than when valves are opened which is 13.1 °C (where water was the heat transfer fluid). Also, it was obtained that the average stored energy by phase change material increased by 18.88% when using oil as heat transfer fluid compared to water. Sharma et al. [107] presented a review on the available thermal energy storage that can be incorporated with solar cooker.

3. Parameters effecting solar cookers performance

The thermal performance of a solar cooker is highly influenced by its main components. Thus, it's obvious that geometry of the cooker determines its performance. The geometry parameters are: booster mirrors, glazing, and absorber plate, cooking pots, heat storage materials and insulation [108].

3.1. Booster mirror

A booster mirror is important in solar cooker since it makes cooking in low ambient temperature possible. It provokes higher working temperatures by permitting higher lightening intensity on the aperture area, thus enhancing the efficiency. Utilizing booster mirrors reduces cooking time since it reflects the extra radiation on the surface of the cooker. Fig. 9 presents a schematic diagram of solar box cooker with three reflectors.

El-Tous et al. [109] performed experiment on tracking system which is progressed to promote solar heating in solar cooker. Solar heater was rotated to track the sun by electronic sun tracking device. The results obtained from comparing fixed and sun tracking cooker revealed that the heating temperature increase by 36% when utilizing sun tracking. It was also found that utilizing sun tracker increases the pot water temperature and decreases the thermal capacity of the water by rising the evaporation rate. The authors concluded that the amount

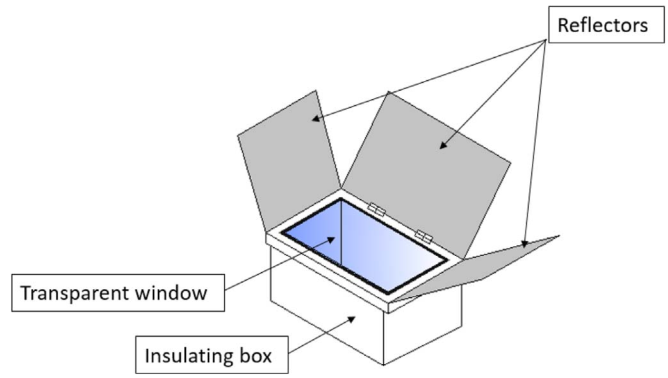

Fig. 9. Solar box cooker with three reflectors. /.

of solar intensity was increased by 20% when tracking sun on the cooker. M. B. Kahsaya et al. [72] compared between solar box cookers with and without internal reflector. The two types of cookers were modeled theoretically by taking into consideration the radiation, convection and conduction heat transfer. Steady state heat transfer analysis of the cooker was employed in the theoretical analysis. Also, experiments have been done to compare the two cookers made up of same materials (except internal absorber) and have same aperture area. The theoretical analysis foresees that utilizing internal reflector will enhance performance of a solar cooker. It was revealed by steady state analysis that the bottom absorber plate temperature in cooker with reflector is higher than that of cooker without reflector. Also, dry test and water boiling tests showed better performance for cooker with reflector. It was found that cooker with reflector has standard stagnation temperature and cooking power higher than that for cooker without reflection. Also, it was concluded that enhancing the performance of box solar cooker can be achieved by making suitable angle side walls of the absorber and utilizing internal reflector. Farooqui [110] performed experiment and numerical simulations to determine the performance parameters of dual booster mirror solar box cookers of three different lengths to width ratios. Also, the optimal tilt angle for both booster mirrors of each day of the year was determined for free tracking operation. Numerical investigation has been performed for 25° latitude location for all days of the year in order to specify the best power collection capability of such cooker during 6 h of the favorable period of cooking which range between 3 h before and after the solar noon. The selected solar cookers for this investigation have 1.33, 2.66 and 3.99 length to width ratios. The experiments have been conducted for 3 days to compare performance of three cookers simultaneously with regular water load. The experimental results has been analyzed to specify the first and second figures of merit, cooking power, quality factor and exergy efficiency for each cooker. It was concluded that the optimum performance of fully loaded solar box cookers with two booster mirrors tilted at suitable angle is attained with aspect ratio of 2.66. Zamani et al. [111] designed two similar solar cookers and experimentally studied the impact of flat and parabolic surfaces on the performance of double exposure solar cookers. The obtained results reveal that the performance of the solar cooker was affected by about 18.5% by flat mirrors on the box part, while about 25% by the mirrors located on the parabolic curve. The authors deduced that the parabolic part has more considerable influence on the performance of solar cooker compared to the box part.

3.2. Glazing

In a solar cooker solar radiation passes through glazing which is utilized to reduce convection losses from the absorber plate by suppressing the static air layer between the absorber plate and the glass. Also, glazing serves in minimizing radiation losses by which it is transparent to short wave radiation (coming from the sun) but opaque to long wave thermal radiation (emitted from absorber plate). Glazing comprises glass, fiberglass, acrylic and other materials. Badar et al. [112] investigated the thermal performance of double glazed solar oven. Experiments were done and the temperatures inside the box cavity are recorded on different days and times with diverse intensities of solar radiation available. Also, steady state heat transfer numerical model is carried out on solar oven without reflector. Based on the experiments and numerical calculations, a parametric study is performed to evaluate the impact of several parameters on the thermal performance of the oven such as distance between glazing, number of glazing, etc. Regarding number of glazing, it was found that higher box temperature is achieved when using double glazing than single glazing. Ghosh et al. [113] studied the thermal performance of a solar cooker with special cover glass of low-e antimony doped indium oxide (IAO) coating. The study was conducted by comparing this solar cooker with a solar cooker uncoated glaze soda lime silicate glass cover, then comparing it with the same solar cooker with evacuated glazed cover attaining vacuum of 10^{-3} atm in the glazing system. At ambient condition, the thermal performance of solar cookers was distinct due to the fluctuation of heat flow through different glazing systems. The thermal performance of a solar cooker box with single glazed low-e IAO coated glass cover was favorable. Thus, solar cooker with low-e IAO coated single glass cover is better preferable.

3.3. Absorber tray

Absorber plate is a key point of solar cooker where cooking process depends on its ability to absorb the useful energy from sun. Solar radiation crosses the glazing of a solar cooker and clashes the high absorptivity absorber surface. Then the tray absorbs high quantity of this energy and transmits it to the food placed in the cooking pot to be cooked. The absorber tray must be painted in black to maximize amount of solar radiation that can be absorbed [114]. Also, it is well known that the geometric structure of the absorber tray is crucial regarding increasing the intensity of light falling and promoting heat transfer to the food in the cooking pot. Zamani et al. [115] interestingly stated that, optimization of absorber plate is one of the most adopted and investigated strategies in the field of optimizing thermal and radiation performance. Besides, Harmim et al. [116] developed experimental work to compare the performance of two solar box cookers; the first one is provided with finned absorber tray while the absorber plate of the second one is without fins. The results revealed that if thermal fins were added to absorber plate of solar box cooker, the temperature will increase by 7% and the boiling time will be minimized by 12% in comparison with solar box cooker of absorber plate without fins.

3.4. Cooking equipment

Cooking vessels are components of solar cooker that are in direct contact with the absorber plate. Both serves in receiving the absorbed useful energy and transmitting it to the food. Various shapes of cooking pots can be utilized, however, the rectangular and cylindrical shaped cooking utensils that are made up of aluminum or copper are recommended. The cooking pot is painted black from outside and placed in the center of the absorber tray to rise the rate of heat transfer by conduction between them. The quantity and nature of food cooked determines the number of cooking vessels.

Sethi et al. [117] evaluated the performance of an inclined box solar cooker with single supporter mirror designed with a novel parallelepiped cooking pot for better cooking efficiency during winter conditions. The new parallelepiped shaped design is specialized by longer inclined south wall and trapezoidal shaped cavity on the pot cover which maximize heat transfer to the food. The performance parameters of this cooker (inclined cooker with parallelepiped cooking vessel) are compared with similar cooker of cylindrical pot design and horizontally placed, in January 2010 (winter month) at Ludhiana climate (30°N 77°E), India. The results revealed that the first and second figures of merit (F1 and F2) for inclined cooker were 0.16 and 0.54 greater than that for horizontally located cooker (0.14 and 0.43). Time taken to boil water and the cooking power was 37% less and 40% more respectively in parallelepiped shaped cooking pot of inclined cooker compared to cylindrical vessel of horizontally located cooker. Hermelinda and Mauricio [118] proceeded in developing jorhejpatarnskua, which is a solar cooker integrated with compound parabolic concentrator. Several tests were performed using several pots simultaneously to study and analyze thermal standards of the cooker. The results unveiled that as cooking pots increase, cooking power, thermal efficiency and second merit decrease to the half in case of two pots and one third in case of three containers. Misraa and Aseri [119] presented a comparative experimental study to enhance performance of solar box cooker. Experiments were conducted on two solar cookers of different cooking environments: natural convection and forced convection heat transfer solar cookers. The experimental results of thermal performance tests showed that the stagnation absorber plate temperatures were 133.9 °C and 119.3 °C and the boiling times for heating 1 kg of water were 52 min and 75 min, for forced and natural convection solar cooker, respectively. Also, it was obtained that forced convection solar cooker cooked rice with higher quality compared to the cooked rice by natural convection solar cooker. It was concluded that forced convection solar cooker has the ability to cook food with good quality and much less time compared to natural convection solar cooker. Hence, performance of solar cooker can be improved by utilizing a small fan to the cooker and achieve forced convection.

3.5. Heat storage material

It is well recognized that solar cookers are elegant application of solar energy that will have a significant potential in the future. But such technology still has some impediments which requires a lot of studies and researches. One of the most critical obstructions challenging solar cookers is their disability to achieve successful cooking process when the sun fades. In most cases, such problem was solved by using phase change materials in order to store energy and use it when there is no enough solar energy. Fig. 10 presents a schematic diagram of an indirect solar cooker with heat storage material (PCM).

Saxena et al. [120] presented various types of phase change materials used in solar cookers. An experiment is done by comparing simple solar box cooker using stearic acid with another solar cooker of similar design but with no phase change material. It was found that among the phase change materials stearic acid is a pleasant choice for storing latent heat. Mussard [121] experimentally compared between the cooking performance of a widespread SK14 cooker and a prototype of parabolic trough solar concentrator cooker with heat storage. The first cooker is direct type solar cooker where the cooking utensil is located on the central point of the dish. In the second cooker working fluid (thermal oil) circulates and transmits heat from the absorber to the storage unit where cooking is achieved at the top of the storage. Boiling and frying tests are conducted to evaluate the efficiency of heat storage system. In addition to that, simulations are performed for progressing and optimizing the system. It was found that cookers with

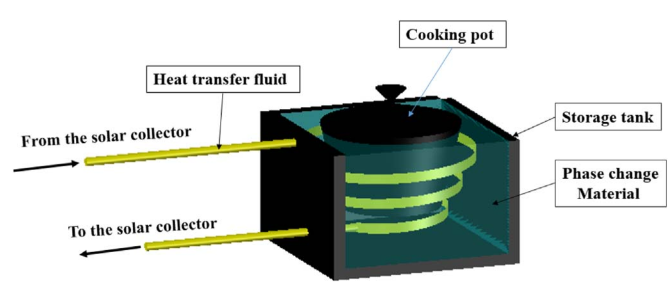

Fig. 10. Indirect solar cooker with heat storage material (PCM).

heat storage system of optimized surface contact have the best performance compared to standard cooker or any other cooking appliances. Chaudhary et al. [122] experimentally investigated solar cooker integrated with parabolic dish collector and phase change thermal storage unit (acetanilide is the phase change material). Experimental setup was performed on three solar cookers: ordinary solar cooker, solar cooker with outer surface painted black, and solar cooker with outer surface painted black along with glazing. The experimental results manifested that the maximum temperature of phase change material attained in ordinary solar cooker, solar cooker with outer surface painted black, and solar cooker with outer surface painted black along with glazing was 119 °C, 175.4 °C and 186.3 °C respectively. Also, it was found that in solar cooker with outer surface painted black and solar cooker with outer surface painted black along with glazing, phase change material stored 26.8% and 32.3%, respectively, more heat compared to that in ordinary solar cooker. The authors concluded that solar cooker with outer surface painted black along with glazing has the best performance compared to ordinary solar cooker and solar cooker with outer surface painted black.

3.6. Insulation

One of the most essential components of solar cookers is insulation which reduces interaction between solar cooker and the environment. It allows maximizing the amount of heat energy stored and thus working more efficiently. To minimize the transmission of heat energy from the cooker to the surrounding, it is mandatory to utilize insulating materials. Insulation can be achieved by using any material of low thermal conductivity, but the selection relies on the lower cost.

Aremu and Akinoso [123] studied the impact of insulating materials on the performance of solar heater. A box solar heater using domestic agricultural insulations is presented. The usage of coconut coir leads to achieve temperature up to 159 °C. Also, it was obtained that during dry season the shortest duration to heat 1 L and 1.5 L of water was 50 and 65 min respectively, and 120–170 min to boil 1 L of water during wet season. It was concluded that performance of agricultural insulations are more efficient than manufactured insulating materials and serves in decreasing the cost of solar box heater. Also, Aremu and Igbeka [124] evaluated energy and exergy efficiencies of solar box cooker with diverse insulating materials. Experiments have been carried out on five solar box cookers with maize cob, air (control), maize husk, coconut coir and polyurethane foam, at Department of Agricultural and Environmental Engineering, for 3 years. Water heating test was used to evaluate energy and exergy of the cookers and the results were analyzed by using ANOVA. It was reported that a solar cooker with air as insulation has the lowest energy and exergy efficiencies (11% and 1.07% respectively) compared to others. This proves the fundamental of using good insulating material for solar box cooker. Mussard and Nydal [125] conducted two tests on solar cooker of heat storage coupled with a self-circulating solar parabolic trough filled with thermal oil. In the first experiment the receiver tube is not insulated while in the second it is insulated with glass tube of 7 mm thickness. Results noted that insulating the absorber tube is not necessary at low temperature and the efficiency is higher in the non-insulated tube. However, glass tube is needed as the storage temperature becomes high and reaches 200 °C, where above it is difficult to gather heat without insulating the absorber.

4. Energy and exergy analysis

Solar cooking is an adequate process of utilizing solar energy to meet cooking request. Many researchers tried to compare and evaluate solar cookers in order to acquire the best performance. Energy and exergy analysis [126,127] is one of the most significant means of studying and evaluating the performance of solar cookers [128].

Panwar et al. [129] stated that energy analysis is based on the first law of thermodynamics, in which the net heat provided is transformed into work. In a solar cooker, energy input depends on collector size and solar intensity, while energy output relies on quantity of cooking fluid and number of cooking pots placed on the absorber tray [130]. The energy efficiency η is defined as the ratio of output energy (E_o) to the input energy (E_i) of solar cooker and it is shown in the following equation [129]:

$$\eta = \frac{output\ energy}{input\ energy} = \frac{E_o}{E_i} = \frac{m_w C_{p,w}(T_{wf} - T_{wi})}{I_t A_{sc} \Delta t} \tag{1}$$

where Cp_w is water specific heat, T_{wf} is final temperature of water, T_{wi} is initial temperature of water, t represents the time, I_t is the total instantaneous solar radiation and A_{sc} is intercept area of solar cooker.

Panwar [131] reported that the concept of exergy is based on first and second law of thermodynamics. Exergy input and output analysis allow finding the locations of the maximum degraded energy of solar cooker. Exergy is defined as the maximum amount of work that can be achieved from a system. The exergy efficiency ψ of a solar cooker is the ratio of output exergy (E_{xo}) to the input exergy (E_{xi}) [128]. It can be calculated using the following equation [130]:

$$\psi = \frac{outputexergy}{inputexergy} = \frac{E_{xo}}{E_{xi}} = \frac{m_w C_{p,w}\left[(T_{wf} - T_{wi}) - \left(T_o \ln\left(\frac{T_{wf}}{T_{wi}}\right)\right)\right]}{I_t A_{sc}\left(1 - \frac{4T_a}{3T_s}\right)} \tag{2}$$

where T_o is the outside temperature, T_a is the ambient temperature and T_s is the sun temperature. Exergy analysis is qualitative estimation of energy while energy analysis is quantitative estimation of energy. It can be said that for predicting the efficiency of a solar cooker, exergy analysis is more convenient than energy analysis. Farooqui [132] presented a review in indirect type vacuum tube based solar cooker. Also, energy and exergy analysis of single vacuum tube based prototype has been performed experimentally. Three experiments has been done within 10 days during March and April 2013. It was obtained from the performance parameter that the cooker has high peak exergy power (55.6 W), 0.042 quality factor, 20–30% energy efficiency and 4–6% exergy efficiency. Also, Farooqui [133] experimentally investigated the effect of varying load on energy and exergy efficiencies and other diverse performance measuring parameters. Five experiments have been performed with variable water loads (range of 3–7 kg), on 14, 15, and 31 of March, 26 and 27 of November 2014. It was obtained that the maximum energy efficiency range is 20–25%, maximum exergy efficiency range remained 2.3–3.8%, maximum exergy output power was 46.4 W and peak exergy output power versus temperature difference was 51.07 W which are the highest compared to other solar cookers. Thus, it was concluded by Farooqui [132,133] that despite its compact size, vacuum tube type solar cooker is comparable to other single family cooker types. Park et al. [134] presented a comprehensive review on energy and exergy analyses of typical renewable energy systems such as solar thermal, solar photovoltaic and biomass cook stove system. The authors concluded that energy analysis is the basic analysis for renewable energy systems. Moreover, the authors found that the performance relied on exergy analysis is lesser than that of energy analysis for all renewable energy systems.

5. Economic and environmental concerns

Solar cooker is a promising option of solar energy appliances. It plays a key role in progressing life and making it healthier. Precisely, solar cooker has a significant influence and benefits that has to do with environment, economic and health.

Solar cookers reduce the dependence on conventional sources of energy and thus lower emissions of greenhouse gases which reduce pollution. As a result, humans become healthier and distant from diseases that are in high rate these days due to pollution. From an economic view, usage of renewable source of energy application (solar cooker) will decrease the increased cost of fossil fuel and will serve in saving a great amount of money. Also, when disease diminish, money spent on medical treatments will also be economized which is a privilege for people. In addition to that, solar cookers minimize utilization of fire wood which reduce deforestation and desertification. Besides, solar cookers decrease the release of smokes from firewood that are harmful to eyes and respiratory system as well, especially for children. In places like Africa, there is a high dependence on wood stoves which are used indoor and outdoor. Indoor pollution resulted from the incomplete combustion of wood generates carbon monoxide gas which is harmful to lungs. Thus, utilization of wood stoves is the main reason of many diseases especially lung cancer, and other respiratory diseases like asthma, etc.

Sosa et al. [135] presented a project implementing prototypes of solar cookers with compound parabolic concentrators in Mexico. It was aimed from this project to reduce timber resource extraction through harnessing renewable energy sources. This reduction was predicted to be 30%. Interviews has been done and showed that 85% of beneficiaries have utilized solar cookers. It was found from the monitoring results that despite the fact that each family expended about 145 kg fuel wood per 1 week, 43% of households have been economizing 50% fuel wood by using solar cooker. This study successfully highlighted the necessity to utilize solar cooker instead of fire wood for human and environmental care in addition to economic benefit.

Succinctly, solar cooker is a gracious application of solar energy. It is friend environment, produces food of high value of nutrition, and it is cheap and convenient for all economic levels of people in society.

5.1. Economic analysis

Referring to the aforementioned comments, solar cooker has an appreciable economic impact. A study is performed to evaluate the amount of saved money if a solar cooker is utilized instead of traditional LPG (Liquefied Petroleum Gas) cooker. Then, the payback period is computed according to the cost of the solar cooker and the amount of saved money. In this study, several types of solar cookers are taken under study and different scenarios in Lebanon country are considered including residential apartment, restaurant, snack and hotel. A survey was done to measure the amount of LPG consumed in each scenario. The survey was perfumed with several number of people having residential apartment, restaurant, snack or hotel. After estimating the amount of LPG, the cost of LPG is calculated for each scenario. The calculation is based on the price in the Lebanese market where the cost of 1 kg of liquefied petroleum gas is approximately $0.91. Table 1 illustrates the consumed amount of LPG (kg/month) and its cost ($/month) for each scenario.

To calculate the payback period for the different solar cooker types, the saved money SM is calculated as follows:

$$smpm = P_r \, . \, M_{lpg} \, . \, P_{lpg} \tag{3}$$

where *smpm* is the amount of saved money per month, P_r is the percentage of time where the SC is used, M_{lpg} *is the mass of LPG* consumed per month and P_{lpg} the price 1 kg of LPG. Hence, the payback period *pbp* is calculated as follow:

$$pbp = \frac{scc}{smpm} \tag{4}$$

where scc is the total cost of solar cooker.

Table 2 illustrates different types of solar cookers with their cost in $. Table 3 shows the amount of money saved for each scenario by considering P_r = 0.5. Table 4 reports the number of solar cookers needed, total cost and the payback period for each solar cooker and for different scenarios.

The number of required solar cookers varies according to the type of solar cookers where each solar cooker accommodates specific number of cooking pots. For example, four cooking units can be placed in solar box cooker while only one pot can be located in a parabolic solar cooker. Also, the cooking site determines the number of needed solar cookers. For instance, hotel and restaurant need more solar cookers than home or snack. Therefore, the number of solar cookers determines the total cost of solar cookers in each scenario. As shown in Table 4, regardless to the type of the solar cooker, the payback period for home is the highest compared to other scenarios, while restaurant has the lowest payback period. On the other hand, regardless to the cooking site, parabolic solar cooker and indirect evacuated solar cooker have the highest payback period due to the fact that they have high cost, and solar parabolic cooker accommodates one cooking pot which requires more than one cooker in some scenarios and thus increases its cost. While solar box and panel cookers has the lowest payback period knowing that solar panel cooker has low cost, and solar box cooker accommodates four pots which decreases number of needed cooker and thus the cost. But in general, payback periods are low, where the highest is for parabolic solar cooker in home (about 6 year and 5 months).

Table 1
Amount of liquefied petroleum gas used and its cost for each scenario.

	Amount of LPG (kg/month)	Cost of LPG ($/month)
Home	20	18.2
Restaurant	2000	1820
Hotel	1320	1201.2
Snack	300	273

Table 2
Different types of solar with their cost.

Solar cooker	cost ($)
Box	350
Panel	86
Parabolic	349
Indirect evacuated tube with thermal storage	640

Table 3
Saved money for each scenario.

Scenario	Saved money ($/month)
Home	9.1
Restaurant	910
Hotel	600.6
Snack	136.5

Table 4
Payback period for each solar cooker and for different scenarios.

solar cooker	Scenario	Number of solar cookers required	Total cost of solar cookers	Payback period (month)
Box	Home	1	350	39
	Restaurant	2	700	1
	Hotel	2	700	2
	Snack	1	350	3
Panel	Home	2	172	19
	Restaurant	6	516	1
	Hotel	6	516	1
	Snack	4	344	3
Parabolic	Home	2	698	77
	Restaurant	6	2094	3
	Hotel	6	2094	4
	Snack	4	1396	11
Indirect evacuated tube with thermal storage	Home	1	640	71
	Restaurant	2	1280	2
	Hotel	2	1280	3
	Snack	1	640	5

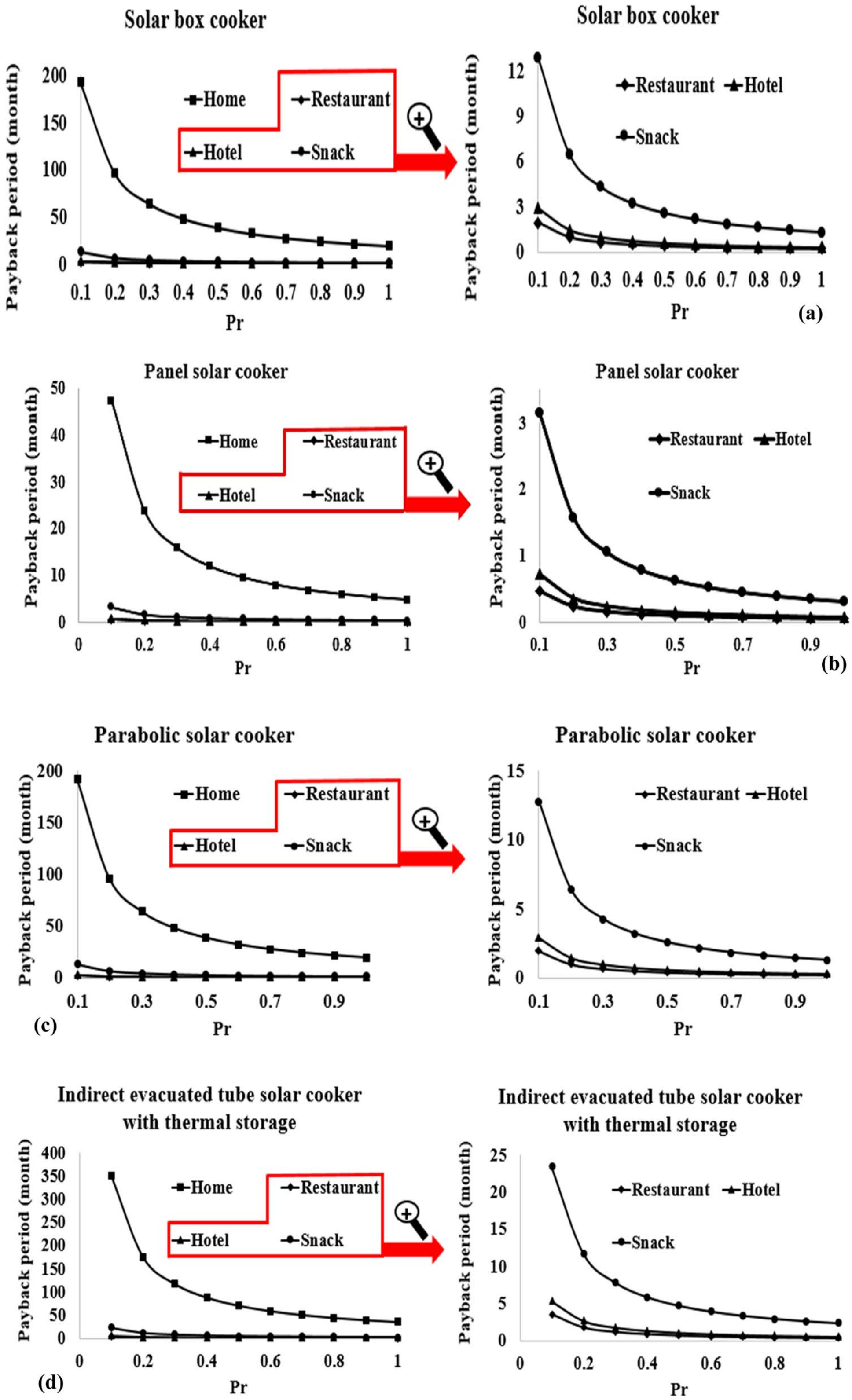

Fig. 11. Variation of payback period as function of Pr and scenarios for (a) solar box cooker (b) solar panel cooker (c) solar parabolic cooker (d) indirect evacuated tube solar cooker with thermal storage.

For Pr = 0.5, the amount of payback period in home is 39 months if solar box cooker will be used, 19 months for solar panel cooker , 77 months for solar panel cooker and 71 months for parabolic solar cooker. Thus, solar panel cooker is the best choice to be used at homes and hotels. Similarly, solar box cooker and solar panel cooker are better to be used at restaurants and snacks. The choice of a solar cooker depends here on the economic side, regardless to the cooker efficiency and performance.

Fig. 11 shows variation of payback period as function of Pr and scenarios for (a) solar box cooker (b) solar panel cooker (c) solar parabolic cooker (d) indirect evacuated tube solar cooker with thermal storage. It can be easily noticed that the payback period is inversely proportional to *Pr*. For example, for solar box cooker, when Pr was 0.2 the payback period was about 96 months, 1 month, 2 months, and 7 months respectively for home, restaurant, hotel and snack. However, when Pr was 0.8 the payback period was approximately 24 months, 0.5 month, 1 months, and 2 months respectively for home, restaurant, hotel and snack.

5.2. Environmental analysis

From an environmental point of view, a solar cooker can highly decrease the amount of produced carbon dioxide gas (CO_2) per year [136].

Panwar et al. [137] interestingly shed light on fuel replacement and carbon dioxide reduction by investigating techno-economic study on animal feed solar cooker in rural areas of India. The results showed that, in 1 year, carbon dioxide emission was decreased by 424.8 kg when using animal feed solar cooker, where the fuel (wood) cost is almost negligible with respect to LPG. Xu et al. [67] discussed methods to minimize carbon footprint of cooking operations according to life cycle assessment methodology. Types of food, fuels, and cookware, correct use and management of cookware, and cooking waste were carried on to study their effect on decreasing carbon footprint. He et al. [3] stated that in China, the government supported energy conservation targets and renewable energy utilization to decrease release of carbon intensity by 17% during years 2011–2015, and reach this decrease to 40–50% by year 2020 where the peak will be attained by year 2030.

To quantify the environmental impact of solar cookers, a study on the amount of carbon dioxide gas (CO_2) produced from the combustion of liquefied petroleum gas in home, restaurant, hotel and fast food restaurant in Lebanon country is carried out. Indeed LPG is mainly formed of butane and propane in addition to other natural gases. In this study, LPG is considered to undergo complete combustion and formed of about 80% of butane and 20% of propane. Eqs. (3) and (4) represent the complete combustion equation of butane and propane respectively.

$$2C_4H_{10} + 13(O_2 + 3.76N_2) \rightarrow 8CO_2 + 10H_2O + 48.88N_2 \quad (5)$$

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.8N_2 \quad (6)$$

According to stoichiometric proportion of these two equations, for every 1 kg of butane and propane 3.0345 kg and 3 kg of Carbone dioxide is produced respectively. Table 5 illustrates the amount of LPG used (kg/month), amount of butane and propane existing in this LPG and the amount of produced carbon dioxide.

The amount of carbon dioxide reduced $M_{reduced\ CO2}$ (due to the utilization of a solar cooker instead of conventional LPG cooker) can be calculated as follow:

$$M_{reduced\ CO_2} = P_r\ .\ M_{CO_2 total} \quad (7)$$

Where $M_{co2,\ total}$ is the total amount of carbon dioxide produced (kg/month).

Fig. 12 sheds light on the amount of carbon dioxide that will be reduced when traditional LPG cooker is replaced by a solar cooker. If a solar cooker is utilized during 50% of cooking time, 30.27, 3027.6, 1998.21 and 454.14 kg/month of carbon dioxide will be reduced in home, restaurant, hotel and snack respectively. While 60.55, 6055.2, 3996.43 and 908.28 kg/month of carbon dioxide will be reduced in home, restaurant, hotel and snack respectively if cooking depends only on solar cooker ($P_r = 1$). Thus, less carbon dioxide will be formed when the percentage of time where a solar cooker is used increase. This study ensures that solar cooker is environmentally friendly, where it serves in reducing emission of carbon dioxide which is polluting gas.

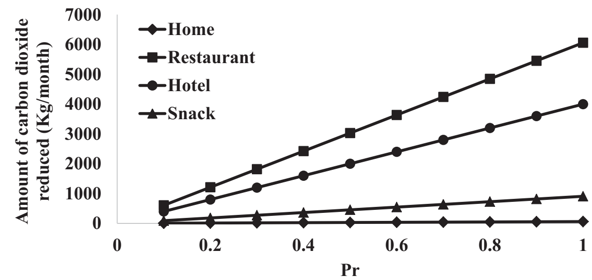

Fig. 12. Amount of carbon dioxide reduced for different values of P_r.

6. Conclusions

The present work call into question the use of solar cookers. It presents a review on the fundamentals of solar cookers with a detailed description of the influence of several key-parameters on their performance. Energy and exergy analysis is presented and environmental and economic studies are developed.

The economic study is carried out to compute the payback period for different solar cookers (solar box cooker, solar panel cooker, parabolic solar cooker and evacuated tube solar cooker with thermal storage) and for several scenarios in Lebanon (home, hotel, restaurant and snack), where *Pr* is varied from 0.1 to 1. The results confirmed that there is inversely relationship between *Pr* and payback period (for all solar cookers and scenarios). To exemplify for solar box cooker, the payback period decreased from 96 to 24 months, 1 to 0.5 months, 2 to 1 month, and from 7 to 2 months in home, restaurant, hotel and snack when *Pr* increased from 0.2 to 0.8.

The environmental study was developed on the previously stated scenarios to shed light on the impact of utilizing solar cookers on carbon dioxide production. It was shown that solar cookers serve in reducing carbon dioxide emissions and there is direct relation between *Pr* and reduction in carbon dioxide production. To illustrate, the amount of carbon dioxide minimized increased from 30.27 to 60.55 kg/month, 3027.6 to 6055.2 kg/month, 1998.21 to 3996.43 kg/month and from 454.14 to 908.28 kg/month in home, restaurant, hotel and snack respectively when *Pr* increased from 0.5 to 1.

It is obvious that solar cooker has a great beneficial impact on economic, health and environment. That is why it is expected that the use of solar cookers will spread all over the world especially in countries such as Lebanon.

Governments and social associations should play an essential role in recommending the more adapted type of solar cooker depending on the weather conditions and local cost of components.

Safety of solar cooker is a crucial issue that should be taken into consideration especially when oil working fluid is used.

Table 5
Total amount of carbon dioxide produced from combustion of LPG.

	Amount of LPG (kg/month)	Amount of butane (kg/month)	Amount of propane (kg/month)	Amount of CO2 formed from butane (kg/month)	Amount of CO2 formed from propane (kg/month)	Total amount of carbon produced (kg/month)
Home	20	16	4	48.55	12	60.55
Restaurant	2000	1600	400	4855.2	1200	6055.2
Hotel	1320	1056	264	3204.43	792	3996.43
Snack	300	240	60	728.28	180	908.28

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